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The objectives of this study were to determine the state-of-the-art of thermal destruction of industrial toxic waste, and to identify and prioritize research needs in this area. Through a literature search, discussion with EPA personnel, discussions with authorities in the area of thermal destruction, and attendance at a national meeting on the subject, the state-of-the-art of thermal destruction of industrial toxic waste has been determined, and research needs which may be expected to provide useful results have been identified.

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ABSTRACT

The objectives of this study were to determine the state-of-the-art of thermal destruction of industrial toxic waste, and to identify and prioritize research needs in this area. Through a literature search, discussions with EPA personnel, discussions with authorities in the area of thermal destruction, and attendance at a national meeting on the subject, the state-of-the-art of thermal destruction of industrial toxic waste has been determined, and research needs which may be expected to provide useful results have been identified.

EXECUTIVE SUMMARY

The objectives of this study were to determine the state-of-the-art of thermal destruction of industrial toxic waste and to identify and prioritize research needs in this area. Through a literature search, discussions with Environmental Protection Agency (EPA) personnel, discussions with authorities in the area of thermal destruction, and attendance at a national meeting on the subject, the state-of-the-art of thermal destruction of industrial toxic waste has been determined, and research needs which may be expected to provide useful results have been identified. Specific recommendations for research programs as determined by this task group study are as follows:

1. Continue and expand the Thermal Decomposition Analytical System (TDAS) studies to determine values of the temperature required to obtain a 99.99 percent destruction efficiency at a residence time of two seconds and general temperature/residence time thermal decomposition data for a variety of hazardous compounds representing different molecular structures.
2. Generate Auto Ignition temperature (AIT) values for the substances studied in (1) and determine the degree of correlation between AIT and T99.99/2.
3. Generate ionization energy data for the substances studied in (1) and determine the degree of correlation between ionization energy and T99.99/2.
4. Attempt to determine the effects of molecular structure on T99.99/2 values.
5. As a part of the TDAS study, examine the concentration of carbon monoxide (CO) as a function of temperature and residence time to determine if regulations governing the thermal destruction of CO will suffice to govern the thermal destruction of all products of incomplete combustion (PICS).

6. Investigate the possibility of monitoring only CO to certify an incinerator for burning toxic wastes.
7. Continue development and implement the EPA rotary kiln pilot plant in Arkansas and use the generated data to develop scale-up laws for rotary kiln incinerators.
8. Develop a pilot plant as in step (6) for the generation of scale-up laws for liquid injection incineration.
9. Pursue the newer approaches to reactive turbulent flow modeling in the presence of large density gradients. Virtually all the extant turbulent modeling is not predictive when one attempts to apply it to a turbulent diffusion flame.
10. Fundamental kinetic studies in which individual reaction steps are identified and each of their rates measured would not be useful at this time. This is because in practical incineration, turbulence so restricts the rate of the chemistry that it controls the conversion rate. Also, the combustion chemistry of large organic molecules is a very complex subject and detailed mechanisms have not been identified as yet. Thus it appears that the simple first order kinetic approach that has been used in the TDAS studies will be adequate for a considerable period of time.

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SECTION 1

INTRODUCTION

Our modern technological society produces large quantities of industrial wastes. Some industrial classifications and types of wastes generated are listed in Table 1. Typical industrial waste production rates are listed in Table 2. A sizable fraction of this waste is considered hazardous, i.e. an estimated 57 million metric tons in 1980 (3).

Toxic chemical wastes in the environment represent one of the most serious problems facing society today. Ever-increasing quantities of these toxic residues have overburdened the receiving environment (air, water, and land) and in many cases, it can no longer handle the increased rate of industrial waste generation and disposal. Lack of adequate process waste disposal facilities is not only aggravating environmental problems, but is forcing some industries to close or restrict certain operations (4).

The need for proper disposal and control of toxic wastes is well recognized. Effective control techniques are available but have not been adequately applied in many cases. Land disposal and ocean dumping of toxic substances have caused contamination of and unacceptable interference with the biological systems of streams, rivers, lakes, and oceans. Alternative means for the disposal of industrial toxic wastes include a variety of thermal destruction techniques in which the pollutant is oxidized or pyrolized at a high temperature to produce benign products. Thermal destruction techniques possess several advantages as a hazardous waste disposal technology:

- Toxic components of hazardous wastes can be converted to harmless compounds or, at least, to less harmful compounds.
- Thermal destruction techniques provide for the ultimate disposal of hazardous wastes, eliminating the possibility of problems resurfacing in the future.

TABLE 1. COMBUSTIBLE WASTES GENERATED BY VARIOUS INDUSTRIES (1)

INDUSTRY	WASTES
Ordnance and accessories	Plastics, rubber, paper, wood, cloth, and chemical residues
Food and kindred products	Meats, fats, oils, offal, vegetables, fruits, nuts and shells, and cereals
Textile mill products	Cloth and fiber residues
Lumber and wood products	Scrap wood, shavings, sawdust, plastics, fibers, glues, sealers, paints, and solvents
Apparel and finished products	Cloth, fibers, plastics, and rubber
Furniture (wood)	Same as lumber plus cloth and padding residues
Furniture (metal)	Plastics, resins, rubber, adhesives, cloth, and paper
Paper and allied products	Paper, fiber residues, chemicals, coatings, fillers, inks, and glues
Printing and publishing	Paper, newsprint, cardboard, chemicals, cloth, inks, and glues
Chemicals	Organic chemicals, plastics, rubber, oils, paints, solvents, and pigments
Petroleum	Asphalts, tars, felts, paper, cloth, and fiber
Rubber and miscellaneous plastics	Scrap rubber and plastics, curing compounds, and dyes
Leather	Scrap leather, thread, dyes, oils, and processing and curing compounds
Fabricated metal products	Coatings, solvents, lubricants, and pickling liquors
Machinery (except electrical)	Wood, plastics, rubber, cloth, paints, solvents, and petroleum products
Electrical	Rubber, plastics, resins, fibers, and cloth residues
Transportation	Fiber, wood, rubber, plastics, cloth, paints, solvents, and petroleum products
Professional, scientific controlling instruments	Plastics, resins, wood, rubber, and fibers
Miscellaneous manufacturing	Plastics, resins, leather, rubber, cloth, straw, adhesives, paints, and solvents

TABLE 2. INDUSTRIAL SOILD-WASTE PRODUCTION RATES (2)

INDUSTRY	WASTE PRODUCTION RATE (tons/employee/year)
Meat Processing	6.2
Cannery	55.6
Frozen foods	18.3
Preserved foods	12.9
Food processing	5.8
Textile-mill products	0.26
Apparel	0.31
Sawmills and planning mills	162.0
Wood products	10.3
Furniture	0.52
Paper and allied products	2.00
Printing and publishing	0.49
Basic chemicals	10.00
Chemical and allied products	0.63
Petroleum	14.8
Rubber and plastic	2.6
Leather	0.17
Stone, clay	2.4
Primary metals	24.
Fabricated metals	1.7
Nonelectrical machinery	2.6
Electrical machinery	1.7
Transportation equipment	1.3
Professional and scientific instruments	0.12
Miscellaneous manufacturing	0.14

- The volume of hazardous waste is greatly reduced by thermal destruction.
- Heat recovery makes it possible to recover some of the energy produced by the combustion process.

The Congress of the United States via Section 3004 of Subtitle C of the Resource Conservation and Recovery Act (RCRA) of 1976 (PL94-580) mandated that the Administrator of the U. S. Environmental Protection Agency promulgate regulations establishing performance standards applicable to owners and operators of hazardous waste treatment, storage, and disposal facilities as may be necessary to protect human health and the environment. These standards are to include, but need not be limited to, requirements concerned with (1) operating methods, techniques, and practices; (2) location, design, and construction; and (3) contingency plans for effective action to minimize unanticipated damage that might occur at these facilities. As applied to the incineration of toxic industrial wastes, present regulations require incinerators to achieve a Destruction and Removal Efficiency (DRE) of 99.99 percent for each designated Principal Organic Hazardous Constituent (POHC) in the waste feed. Destruction and removal efficiency for an incinerator/air pollution control system is defined by the following formula:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} (100)$$

where DRE = destruction and removal efficiency, percent;

W_{in} = mass feed rate of the principal organic hazardous constituent(s) to the incinerator;

W_{out} = mass emission rate of the principal organic hazardous constituent(s) to the atmosphere (as measured in the stack prior to discharge).

Thus, DRE calculations are based on the combined efficiencies of destruction in the incinerator and removal from the gas stream in the air pollution control system. Specification of the principal organic hazardous constitutents in a waste is subject to best engineering judgment, considering the toxicity, thermal stability, and quantity of each organic waste constituent. POHC's are identified on the incinerator permit application. To allow for the formation of any hazardous combustion by-products, the EPA has proposed an amendment that the amount of these by-products must not exceed 0.01 percent of the total mass feedrate (5).

For fundamental studies of thermal oxidation processes, a thermal oxidation Destruction Efficiency (DE) is of more use than the DRE. The DE is defined in a fashion similar to the DRE with the exception that W_{out} is defined to be the mass emission rate of the POHC's out of the incinerator combustion stack. Thus, the DE is a thermal oxidation destruction efficiency only and does not include removal by any air pollution control system as does the DRE used in the EPA incinerator regulations.

A great deal of effort is currently being focused on the subject of thermal destruction of toxic industrial wastes. A number of studies, reviews, conferences, and courses dedicated to this topic have appeared recently. A listing of these recent efforts is given in the APPENDIX of this report. The specific objectives of this task group study were to examine the literature on thermal destruction processes in depth in order to determine how well the fundamentals of the processes are understood and to prioritize research needs in the areas of thermal destruction of industrial toxic wastes.

SECTION 2

CLASSIFICATION AND CHARACTERIZATION OF HAZARDOUS WASTES POTENTIALLY TREATABLE BY THERMAL DESTRUCTION

The term "hazardous wastes" covers a wide range of chemicals. Heavy metals, pesticide residues, organic solvents, acids, inorganic salts, explosives--all of these may fall under the heading of "hazardous". Each has its own chemical characteristics; each must be handled differently. Analysis and characterization of wastes is vitally important both from the standpoint of determining the best treatment or disposal strategy and of preventing dangerous reactions which could result from mixing incompatible materials. The most basic chemical waste classification is based on elemental composition. For those wastes potentially treatable by any of the various thermal destruction techniques, four classifications are used. These are listed in Table 3. Difficulty in treating the waste by thermal destruction techniques increases as one progresses from Waste Class 1 to Waste Class 4.

There are two basic types of hazardous wastes which are organic, or partially organic, in nature and which can be incinerated (6):

(1) Combustible wastes, which will sustain combustion without the use of auxiliary fuel; and

(2) Noncombustible wastes, which will not sustain combustion without auxiliary fuel.

Noncombustible types usually contain significant amounts of water or other inert compounds. Either of these wastes may contain small or large amounts of inorganic salts, halogen compounds, nitrogen compounds, sulfur compounds, or phosphorus compounds. Organic materials, whether diluted or concentrated, may be oxidized during incineration if the temperature is high enough, if there is adequate mixing with the combustion air or oxygen, and if

TABLE 3. CHEMICAL WASTE CLASSIFICATIONS (4)

Waste Class	Elemental Composition	Example
1	C,H and/or C,H,O	Tars from production of styrene Off-specification phenol
2	C,H,N and/or C,H,N,O	Solid residue from manufacture of aromatic amines TDI manufacture reactor tar bottoms
3	C,H,Cl and/or C,H,Cl,O	Vinyl chloride monomer manufacturing wastes Phenolic tar from 2,4-D manufacture
4	C,H,N,Cl and/or C,H,Cl,N,O	Nitrochlorobenzene manufacturing wastes
	C,H,S and or C,H,S,O	Petroleum refining sour waste
	C,H,F and/or C,H,F,O	Fluorinated herbicide wastes
	C,H,Br and/or C,H,Br,O	Ethylene bromide manufacturing wastes
	C,H,P and/or C,H,P,O	Malathion
	C,H,Si and/or C,H,Si,O	Tetraethyl orthosilicate wastes
	C,H,Na and/or C,H,Na,O	Refinery spent caustic

the residence time within the incinerator is of sufficient duration. Inorganic materials will form oxides or carbonates and exit from the incineration zone. These materials must then be captured by some device before the remaining flue gases are discharged into the atmosphere. Usually a wet scrubber is used because it is suitable to high temperature conditions. However, the effluent can be cooled so that baghouses, electrostatic precipitators, or similar devices can be applied. Wet electrostatic precipitation or ionized scrubbers offer some advantages because of their lower pressure drop and lower power consumption.

The destruction of halogenated organic wastes requires sufficient hydrogen in the incineration process to hydrolyze the halogen to acid gas which can then be absorbed by water. This can usually be accomplished by the addition of a high-hydrogen fuel or steam. Any free halogen remaining after incineration will have to be neutralized by scrubbing with caustic. Caustic scrubbing is also usually required for hydrogen bromide as it is not easily absorbed in water. The amount of free halogen remaining after incineration is generally a function of temperature and residence time in the incineration chamber.

Oxides of nitrogen formed by the incineration of nitrated organics can be reduced by several approaches. One method is to use a large chamber with a long residence time and a relatively low combustion chamber temperature, and another method is to use two-stage combustion where the primary chamber is operated fuel-rich and the unburned hydrocarbons are subsequently oxidized in the secondary chamber. Formation of NO_x in the high-temperature zone is reduced by removing the oxygen necessary for its formation.

Sulfur from sulfonated organic wastes may be oxidized to sulfur dioxide or sulfur trioxide, both of which may be absorbed in a caustic soda or soda ash solution in a packed tower scrubber to form sodium sulfite or sodium sulfate. Aqueous caustic soda or soda ash may also be injected into the combustion zone to react with sulfur dioxide, forming a sulfite which can be removed by water scrubbing.

Organophosphorus materials can be incinerated with subsequent scrubbing of the P_2O_5, which is formed in the combustion process, by water and/or caustic to form weak phosphoric acid or sodium phosphate.

Table 4 presents a list of hazardous wastes rated as good, potential, or poor candidates for incineration by appropriate technologies. Because rotary kiln, fluidized bed, and liquid injection incineration are at present the most highly developed and most commonly used incinerators for hazardous waste, the recommended incinerator types listed in Table 4 have been limited to these three types, although other thermal destruction techniques may also be appropriate. The criteria used in assigning incineration categories to the various wastes listed in Table 4 are as follows:

Waste containing	Incineration Category
Carbon, hydrogen, and/or oxygen	Good
Carbon, hydrogen, $\leq 30\%$ by weight chlorine and/or oxygen	Good
Carbon, hydrogen, and/or oxygen, $> 30\%$ by weight chlorine, phosphorus, sulfur, bromine, iodine, or nitrogen	Potential
Unknown percent of chlorine	Potential
Inorganic compounds	Poor
Compounds containing metals	Poor

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (3,7)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
Generic							
F001	The spent halogenated solvents used in degreasing, tetrachloroethylene, trichloroeythylene, methylene chloride, 1,1,1-trichloroethane, carbon tetrachloride, and the chlorinated fluorocarbons, and sludges from the recovery of these solvents in degreasing operations		x		x	x	x
F002	The spent halogenated solvents, tetrachloroethylene, methylene chloride, trichloroethylene, 1,1,1-trichloroethane, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, o-dichlorobenzene, trichlorofluoromethane and the still bottoms from the recovery of these solvents		x		x	x	x
F003	The spent nonhalogenated solvents, xylene, acetone, ethyl acetate, ethyl benzene, ethyl ether, n-butyl alcohol, cyclohexanone, and the still bottoms from the recovery of these solvents	x			x	x	x
F004	The spent nonhalogenated solvents, cresols and cresylic acid, nitrobenzene, and the still bottoms from the recovery of these solvents	x			x	x	x
F005	The spent nonhalogenated solvents, methanol, toluene, methyl ethyl ketone, carbon disulfide, isobutanol, pyridine and still bottoms from the recovery of these solvents	x			x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
F006	Wastewater treatment sludges from electroplating operations			x			
F007	Spent plating bath solutions from electroplating operations			x			
F008	Plating bath sludges from the bottom of plating baths from electroplating operations			x			
F009	Spent stripping and cleaning bath solutions from electroplating operations			x			
F010	Quenching bath sludge from oil baths from metal heat treating operations			x			
F011	Spent solutions from salt bath pot cleaning from metal heat treating operations			x			
F012	Quenching wastewater treatment sludges from metal heat treating operations			x			
F013	Flotation tailings from selective flotation from mineral metals recovery operations			x			
F014	Cyanidation wastewater treatment tailing pond sediment from mineral metals recovery operation			x			
F015	Spent cyanide bath solutions from mineral metals recovery operations			x			
F016	Dewatered air pollution control scrubber sludges from coke ovens and blast furnaces			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
Wood preservation							
K001	Bottom sediment sludge from the treatment of wastewaters from wood preserving processes that use creosote and/or pentachlorophenol		x			x	x
Inorganic pigments							
K002	Wastewater treatment sludge from the production of chrome yellow and orange pigments			x			
K003	Wastewater treatment sludge from the production of molybdate orange pigments			x			
K004	Wastewater treatment sludge from the production of zinc yellow pigments			x			
K005	Wastewater treatment sludge from the production of chrome green pigments			x			
K006	Wastewater treatment sludge from the production of chrome oxide green pigments (anhydrous and hydrated)			x			
K007	Wastewater treatment sludge from the production of iron blue pigments			x			
K008	Oven residue from the production of chrome oxide green pigments			x			
Organic chemicals							
K009	Distillation bottoms from the production of acetaldehyde from ethylene		x		x	x	
K010	Distillation side cuts from the production of acetaldehyde from ethylene		x		x	x	

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K011	Bottom stream from the wastewater stripper in the production of acrylonitrile		x		x	x	
K012	Still bottoms from the final purification of acrylonitrile in the production of acrylonitrile	x			x	x	x
K013	Bottom stream from the acetonitrile column in the production of acrylonitrile		x		x	x	
K014	Bottoms from the acetonitrile purification column in the production of acrylonitrile		x		x	x	
K015	Still bottoms from the distillation of benzyl chloride		x		x	x	
K016	Heavy ends or distillation residues from the production of carbon tetrachloride		x			x	x
K017	Heavy ends (still bottoms) from the purification column in the production of epichlorohydrin		x			x	x
K018	Heavy ends from fractionation of ethyl chloride production		x			x	x
K019	Heavy ends from the distillation of ethylene dichloride in ethylene dichloride production		x			x	x
K020	Heavy ends from the distillation of vinyl chloride in vinyl chloride monomer production		x			x	x
K021	Aqueous spent antimony catalyst waste from fluoromethanes production			x			
K022	Distillation bottom tars from the production of phenol/acetone from cumene	x				x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K023	Distillation light ends from the production of phthalic anhydride from naphthalene		x		x	x	x
K024	Distillation bottoms from the production of phthalic anhydride from naphthalene		x			x	x
K025	Distillation bottoms from the production of nitrobenzene by the nitration of benzene		x		x	x	
K026	Stripping still tails from the production of methyl ethyl pyridines		x		x	x	
K027	Centrifuge residue from toluene diisocyanate production		x		x	x	
K028	Spent catalyst from the hydrochlorinator reactor in the production of 1,1,1-trichloroethane			x			
K029	Waste from the product stream stripper in the production of 1,1,1-trichloroethane		x		x	x	
K030	Column bottoms or heavy ends from the combined production of trichloroethylene and perchloroethylene		x			x	x
Pesticides							
K031	By-products salts generated in the production of MSHA and cacodylic acid			x			
K032	Wastewater treatment sludge from the production of chlordane		x			x	
K033	Wastewater and scrub water from the chlorination of cyclopentadiene in the production of chlordane		x		x	x	

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K034	Filter solids from the filtration of hexachlorocyclopentadiene in the production of chlordane			x			
K035	Wastewater treatment sludges generated in the production of creosote		x			x	
K036	Still bottoms from toluene reclamation distillation in the production of disulfoton		x		x	x	
K037	Wastewater treatment sludges from the production of disulfoton		x			x	
K038	Wastewater from the washing and stripping of phorate production		x		x	x	
K039	Filter cake from the filtration of diethylphosphorodithoric acid in the production of phorate		x			x	x
K040	Wastewater treatment sludge from the production of phorate			x			
K041	Wastewater treatment sludge from the production of toxaphene		x			x	
K042	Heavy ends or distillation residues from the distillation of tetrachlorobenzene in the production of 2,4,5-T		x		x	x	
K043	2,6-Dichlorophenol waste from the production of 2,4-D		x		x	x	
Explosives							
K044	Wastewater treatment sludges from the manufacturing and processing of explosives		x			x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K045	Spent carbon from the treatment of wastewater containing explosives	x				x	x
K046	Wastewater treatment sludges from the manufacturing, formulation and loading of lead-based initiating compounds			x			
K047	Pink/red water from TNT operations	x			x	x	x
Petroleum refining							
K048	Dissolved air flotation (DAF) float from the petroleum refining industry	x				x	x
K049	Slop oil emulsion solids from the petroleum refining industry	x				x	x
K050	Heat exchanger bundle cleaning sludge from the petroleum refining industry		x			x	x
K051	API separator sludge from the petroleum refining industry	x				x	x
K052	Tank bottoms (leaded) from the petroleum refining industry		x			x	x
Leather tanning finishing							
K053	Chrome (blue) trimmings generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K054	Chrome (blue) shavings generated by the following subcategories of the leather tanning and finishing industry: hair pump/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling			x			
K055	Buffing dust generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; and through the blue			x			
K056	Sewer screenings generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling			x			
K057	Wastewater treatment sludges generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue and shearling			x			
K058	Wastewater treatment sludges generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; and through-the-blue			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K059	Wastewater treatment sludges generated by the following subcategory of the leather tanning and finishing industry: hair save/nonchrome tan/retan/wet finish			x			
Iron and Steel							
K060	Ammonia still lime sludge from coking operations			x			
K061	Emission control dust/sludge from the electric furnace production of steel			x			
K062	Spent pickle liquor from steel finishing operations			x			
K063	Sludge from lime treatment of spent pickle liquor from steel finishing operations			x			
Primary copper							
K064	Acid plant blowdown slurry/sludge resulting from the thickening of blowdown slurry from primary copper production			x			
Primary lead							
K065	Surface impoundment solids contained in and dredged from surface impoundments at primary lead smelting facilities			x			
Primary zinc							
K066	Sludge from treatment of process wastewater and/or acid plant blowdown from primary zinc production			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
K067	Electrolytic anode slimes/sludges from primary zinc production			x			
K068	Cadmium plant leach residue (iron oxide) from primary zinc production			x			
Secondary lead							
K069	Emission control dust/sludge from secondary lead smelting			x			
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof							
P001	3-(alpha-Acetonylbenzyl)-4-hydroxycoumarin and salts	x			x	x	x
P002	1-Acetyl-2-thiourea		x		x	x	x
P003	Acrolein	x			x	x	x
P004	Aldrin		x			x	x
P005	Allyl alcohol	x			x	x	x
P006	Aluminum phosphide			x			
P007	5-(Aminomethyl)-3-isoxazolol		x			x	x
P008	4-Aminopyridine		x			x	x
P009	Ammonium picrate		x			x	x
P010	Arsenic acid			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P011	Arsenic pentoxide			x			
P012	Arsenic trioxide			x			
P013	Barium cyanide			x			
P014	Benzenethiol		x		x	x	x
P015	Beryllium dust			x			
P016	Bis(chloromethyl) ether		x		x	x	x
P017	Bromoacetone		x		x	x	x
P018	Brucine	x				x	x
P019	2-Butanone peroxide	x			x	x	x
P020	2-sec-butyl-4,6-dinitrophenol	x			x	x	x
P021	Calcium cyanide			x			
P022	Carbon disulfide	x			x	x	x
P023	Chloroacetaldehyde		x		x	x	x
P024	p-Chloroaniline	x				x	
P025	1-(p-Chlorobenzoyl)-5-methoxy-2-methylindole-3-acetic acid	x			x	x	
P026	1-(o-Chlorophenyl) thiourea		x			x	
P027	3-Chloropropionitrile		x		x	x	
P028	alpha-Chlorotoluene	x			x	x	

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P029	Copper cyanide			x			
P030	Cyanides			x			
P031	Cyanogen	x				x	x
P032	Cyanogen bromide		x			x	x
P033	Cyanogen chloride		x			x	x
P034	2-Cyclohexyl-4,6-dinitrophenol	x				x	x
P035	2,4-Dichlorophenoxyacetic acid (2,4-D)		x			x	
P036	Dichlorophenylarsine			x			
P037	Dieldrin	x				x	
P038	Diethylarsine			x			
P039	0,0-Diethyl-S-[2-(ethylthio)ethyl] ester of phosphorothioic acid		x		x	x	x
P040	0,0-Diethyl-0-(2-pyrazinyl) phosphorothioate	x			x	x	x
P041	0,0-Diethyl phosphoric acid, 0-p-nitrophenyl ester		x		x	x	x
P042	3,4-Dihydroxy-alpha-(methylamino)-methyl benzyl alcohol	x			x	x	x
P043	Di-isopropylfluorophosphate		x		x	x	x
P044	Dimethoate		x			x	x
P045	3,3-Dimethyl-1-(methylthio)-2-butanone-0-[(methylamino)carbonyl] oxime		x			x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P046	alpha, alpha-dimethylphenethylamine	x			x	x	x
P047	4,6-Dinitro-o-cresol and salts		x			x	x
P048	2,4-Dinitrophenol		x			x	x
P049	2,4-Dithiobiuret		x			x	x
P050	Endosulfan		x				x
P051	Endrin		x		x	x	
P052	Ethylcyanide	x			x	x	x
P053	Ethylenediamine	x			x	x	x
P054	Ethyleneimine	x			x	x	x
P055	Ferric cyanide			x			
P056	Fluorine			x			
P057	2-Fluoroacetamide		x			x	x
P058	Fluoroacetic acid, sodium salt			x			
P059	Heptachlor		x			x	
P060	1,2,3,4,10,10-Hexachloro-1,4,4a,5,8,8a-hexahydro-1,4:5,8-endo, endo-dimethanonaphthalene		x			x	x
P061	Hexachloropropene		x		x	x	x
P062	Hexaethyl tetraphosphate		x			x	x
P063	Hydrocyanic acid	x			x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P064	Isocyanic acid, methyl ester	x			x	x	x
P065	Mercury fulminate			x			
P066	Methomyl		x			x	x
P067	2-Methylaziridine	x			x	x	x
P068	Methyl hydrazine	x			x	x	x
P069	2-Methyllactonitrile		x		x	x	x
P070	2-Methyl-2-(methylthio)propionaldehyde-o-(methylcarbonyl) oxime		x			x	x
P071	Methyl parathion		x			x	x
P072	1-Naphthyl-2-thiourea		x			x	x
P073	Nickel carbonyl			x			
P074	Nickel cyanide			x			
P075	Nicotine and salts		x			x	x
P076	Nitric oxide			x			
P077	p-Nitroaniline		x			x	x
P078	Nitrogen dioxide			x			
P079	Nitrogen peroxide			x			
P080	Nitrogen tetroxide			x			
P081	Nitroglycerine	x			x	x	x

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EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P082	N-Nitrosodimethylamine		x			x	x
P083	N-Nitrosodiphenylamine		x			x	x
P084	N-Nitrosomethylvinylamine		x			x	x
P085	Octamethylpyrophosphoramide		x			x	x
P086	Oleyl alcohol condensed with 2 moles ethylene oxide	x			x	x	x
P087	Osmium tetroxide			x			
P088	7-Oxabicyclo(2.2.1)heptane-2,3-dicarboxylic acid	x			x	x	x
P089	Parathion		x		x	x	x
P090	Pentachlorophenol		x			x	
P091	Phenyl dichloroarsine			x			
P092	Phenylmercury acetate			x			
P093	N-Phenylthiourea		x			x	x
P094	Phorate		x		x	x	x
P095	Phosgene		x			x	x
P096	Phosphine		x			x	x
P097	Phosphorothioic acid, O,O-dimethyl ester, O-ester, with N,N-dimethyl benzene sulfonamide		x		x	x	x
P098	Potassium cyanide			x			
P099	Potassium silver cyanide			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P100	1,2-Propanediol	X			X	X	X
P101	Propionitrile	X			X	X	X
P102	2-Propyn-1-ol	X			X	X	X
P103	Selenourea			X			
P104	Silver cyanide			X			
P105	Sodium azide			X			
P106	Sodium cyanide			X			
P107	Strontium sulfide			X			
P108	Strychnine and salts		X			X	X
P109	Tetraethyldithiopyrophosphate		X			X	X
P110	Tetraethyl lead			X			
P111	Tetraethylpyrophosphate		X		X	X	X
P112	Tetranitromethane		X		X	X	X
P113	Thallic oxide			X			
P114	Thallium selenite			X			
P115	Thallium (1) sulfate			X			
P116	Thiosemicarbazide		X			X	X
P117	Thiuram		X			X	X

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
P118	Trichloromethanethiol		x			x	x
P119	Vanadic acid, ammonium salt			x			
P120	Vanadium pentoxide			x			
P121	Zinc cyanide			x			
P122	Zinc phosphide			x			
U001	Acetaldehyde	x			x		
U002	Acetone	x			x	x	x
U003	Acetonitrile		x		x	x	x
U004	Acetophenone	x			x	x	x
U005	2-Acetylaminoflourene		x			x	x
U006	Acetyl chloride		x		x	x	x
U007	Acrylamide		x			x	x
U008	Acrylic acid	x			x	x	x
U009	Acrylonitrile	x			x	x	x
U010	6-Amino-1,1a,2,8,8a,8b-hexahydro-8-(hydroxymethyl) 8-methoxy-5-methylcarbamate azirino (2',3':3,4) pyrrolO(1,2-a)indole-4, 7-dione (ester)		x			x	x
U011	Amitrole		x			x	x
U012	Aniline	x			x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U013	Asbestos			x			
U014	Auramine		x			x	x
U015	Azaserine			x			
U016	Benz[c]acridine		x		x	x	
U017	Benzal chloride		x		x	x	
U018	Benz[a]anthracene	x			x	x	x
U019	Benzene	x			x	x	x
U020	Benzenesulfonyl chloride		x		x	x	
U021	Benzidine		x			x	x
U022	Benzo[a]pyrene	x				x	x
U023	Benzotrichloride		x		x	x	
U024	Bis(2-chloroethoxy)methane		x		x	x	x
U025	Bis(2-chloroethyl) ether		x		x	x	x
U026	N,N-Bis(2-chloroethyl)-2-naphthylamine	x				x	x
U027	Bis(2-chloroisopropyl) ether		x		x	x	x
U029	Bromomethane		x			x	x
U030	4-Bromophenyl phenyl ether		x		x	x	x
U031	n-Butyl alcohol	x			x	x	x

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EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U032	Calcium chromate			x			
U033	Carbonyl fluoride		x			x	x
U034	Chloral		x		x	x	x
U035	Chlorambucil		x			x	x
U036	Chlordane		x		x	x	
U037	Chlorobenzene	x			x	x	
U038	Chlorobenzilate	x			x	x	
U039	p-Chloro-m-cresol	x				x	
U040	Chlorodibromomethane		x			x	x
U041	1-Chloro-2,3-epoxypropane		x		x	x	x
U042	Chloroethyl vinyl ether		x		x	x	x
U043	Chloroethene		x			x	x
U044	Chloroform		x		x	x	x
U045	Chloromethane		x			x	x
U046	Chloromethyl methyl ether		x		x	x	x
U047	2-Chloronaphthalene	x				x	x
U048	2-Chlorophenol	x			x	x	
U049	4-Chloro-o-toluidine hydrochloride		x		x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U050	Chrysene	x				x	x
U051	Cresote	x			x	x	x
U052	Cresols	x				x	x
U053	Crotonaldehyde	x			x	x	x
U054	Cresylic acid	x			x	x	x
U055	Cumene	x			x	x	x
U056	Cyclohexane	x			x	x	x
U057	Cyclohexanone	x			x	x	x
U058	Cyclophosphamide		x			x	x
U059	Daunomycin		x			x	x
U060	DDD		x			x	
U061	DDT		x			x	
U062	Diallate		x			x	x
U063	Dibenz[a,h]anthracene	x				x	x
U064	Dibenzo[a,i]pyrene	x				x	x
U065	Dibromochloromethane		x		x	x	x
U066	1,2-Dibromo-3-chloropropane		x		x	x	x
U067	1,2-Dibromoethane		x			x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U068	Dibromomethane		x			x	x
U069	Di-n-butyl phthalate	x			x	x	x
U070	1,2-Dichlorobenzene		x		x	x	
U071	1,3-Dichlorobenzene		x		x	x	
U072	1,4-Dichlorobenzene		x			x	
U073	3,3'-Dichlorobenzidine		x			x	
U074	1,4-Dichloro-2-butene		x		x	x	x
U075	Dichlorodifluoromethane		x			x	x
U076	1,1-Dichloroethane		x		x	x	x
U077	1,2-Dichloroethane		x		x	x	x
U078	1,1-Dichloroethylene		x		x	x	x
U079	1,2-trans-dichloroethylene		x		x	x	x
U080	Dichloromethane		x		x	x	x
U081	2,4-Dichlorophenol		x			x	
U082	2,6-Dichlorophenol		x			x	
U083	1,2-Dichloropropane		x		x	x	x
U084	1,3-Dichloropropane		x		x	x	x
U085	Diepoxybutane	x			x	x	x

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EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U086	1,2-Diethylhydrazine	x				x	x
U087	0,0-Diethyl S-methyl ester of phosphorodithioic acid		x		x	x	x
U088	Diethyl phthalate	x			x	x	x
U089	Diethylstilbestrol	x				x	x
U090	Dihydrosafrole	x				x	x
U091	3,3'-Dimethoxybenzidine	x			x	x	x
U092	Dimethylamine	x				x	x
U093	p-Dimethylaminoazobenzene		x			x	x
U094	7,12-Dimethylbenz[a]anthracene	x				x	x
U095	3,3'-Dimethylbenzidine	x				x	x
U096	alpha-alpha-Dimethylbenzylhydroperoxide	x			x	x	x
U097	Dimethylcarbamoyl chloride		x			x	x
U098	1,1-Dimethylhydrazine		x		x	x	x
U099	1,2-Dimethylhydrazine		x		x	x	x
U100	Dimethylnitrosoamine		x		x	x	x
U101	2,4-Dimethylphenol	x				x	x
U102	Dimethyl phthalate	x			x	x	x

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EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U103	Dimethyl sulfate		x		x	x	x
U104	2,4-Dinitrophenol		x			x	x
U105	2,4-Dinitrotoluene		x			x	x
U106	2,6-Dinitrotoluene		x			x	x
U107	Di-n-octyl phthalate	x			x	x	x
U108	1,4-Dioxane	x			x	x	x
U109	1,2-Diphenylhydrazine		x			x	x
U110	Dipropylamine		x		x	x	x
U111	Di-n-propylnitrosamine		x			x	x
U112	Ethyl acetate	x			x	x	x
U113	Ethyl acrylate	x			x	x	x
U114	Ethylenebisdithiocarbamate		x		x	x	x
U115	Ethylene oxide	x				x	x
U116	Ethylene thiourea		x			x	x
U117	Ethyl ether	x			x	x	x
U118	Ethylmethacrylate	x				x	x
U119	Ethyl methanesulfonate		x		x	x	x
U120	Fluoranthene	x				x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U121	Fluorotrichloromethane		x			x	x
U122	Formaldehyde	x				x	x
U123	Formic acid	x			x	x	x
U124	Furan	x			x	x	x
U125	Furfural	x			x	x	x
U126	Glycidylaldehyde	x			x	x	x
U127	Hexachlorobenzene		x			x	
U128	Hexachlorobutadiene		x		x	x	x
U129	Hexachlorocyclohexane		x			x	x
U130	Hexachlorocyclopentadiene		x		x	x	x
U131	Hexachloroethane		x			x	x
U132	Hexachlorophene		x			x	x
U133	Hydrazine		x		x	x	x
U134	Hydrofluoric acid			x			
U135	Hydrogen sulfide		x			x	x
U136	Hydroxydimethyl arsine oxide			x			
U137	Indeno(1,2,3-cd)pyrene	x				x	x
U138	Iodomethane		x		x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U139	Iron Dextran		x				
U140	Isobutyl alcohol	x			x	x	x
U141	Isosafrole	x			x	x	x
U142	Kepone	x				x	x
U143	Lasiocarpine		x			x	x
U144	Lead acetate			x			
U145	Lead phosphate			x			
U146	Lead subacetate			x			
U147	Maleic anhydride	x				x	x
U148	Maleic hydrazide		x			x	x
U149	Malononitrile		x			x	x
U150	Melphalan		x			x	x
U151	Mercury			x			
U152	Methacrylonitrile		x		x	x	x
U153	Methanethiol		x			x	x
U154	Methanol	x			x	x	x
U155	Methapyrilene		x		x	x	x
U156	Methyl chlorocarbonate		x		x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U157	3-Methylcholanthrene	x				x	x
U158	4,4'-Methylene-bis-(2-chloroaniline)	x				x	x
U159	Methyl ethyl ketone	x			x	x	x
U160	Methyl ethyl ketone peroxide	x			x	x	x
U161	Methyl isobutyl ketone	x			x	x	x
U162	Methyl methacrylate	x			x	x	x
U163	N-Methyl-N'-nitro-nitrosoguanidine		x		x	x	x
U164	Methylthiouracil		x			x	x
U165	Naphthalene	x				x	x
U166	1,4-Naphthoquinone	x				x	x
U167	1-Naphthylamine		x			x	x
U168	2-Naphthylamine		x			x	x
U169	Nitrobenzene		x		x	x	x
U170	4-Nitrophenol		x			x	x
U171	2-Nitropropane		x			x	x
U172	N-Nitrosodi-n-butylamine		x		x	x	x
U173	N-Nitrosodiethanolamine		x		x	x	x
U174	N-Nitrosodiethylamine		x		x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U175	N-Nitrosodi-n-propylamine		x		x	x	x
U176	N-Nitroso-n-ethylurea		x			x	x
U177	N-Nitroso-n-methylurea		x			x	x
U178	N-Nitroso-n-methylurethane		x			x	x
U179	N-Nitrosopiperidine		x		x	x	x
U180	N-Nitrosopyrrolidine		x		x	x	x
U181	5-Nitro-o-toluidine		x			x	x
U182	Paraldehyde	x			x	x	x
U183	Pentachlorobenzene		x			x	
U184	Pentachloroethane		x		x	x	x
U185	Pentachloronitrobenzene		x			x	x
U186	1,3-Pentadiene	x				x	x
U187	Phenacetin		x			x	x
U188	Phenol	x	x			x	x
U189	Phosphorous sulfide		x			x	x
U190	Phthalic anhydride	x				x	x
U191	2-Picoline		x		x	x	x
U192	Pronamide		x			x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U193	1,3-Propane sultone		x			x	x
U194	n-Propylamine		x			x	x
U196	Pyridine		x		x	x	x
U197	Quinones	x				x	x
U200	Reserpine		x			x	x
U201	Resorcinol	x				x	x
U202	Saccharin		x			x	x
U203	Safrole	x			x	x	x
U204	Selenious acid			x			
U205	Selenium sulfide			x			
U206	Streptozotocin		x			x	x
U207	1,2,4,5-Tetrachlorobenzene		x		x	x	x
U208	1,1,1,2-Tetrachloroethane		x		x	x	x
U209	1,1,2,2-Tetrachloroethane		x		x	x	x
U210	Tetrachloroethane		x		x	x	x
U211	Tetrachloromethane		x			x	x
U212	2,3,4,6-Tetrachlorophenol		x			x	x
U213	Tetrahydrofuran	x			x	x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U214	Thallium acetate			x			
U215	Thallium carbonate			x			
U216	Thallium chloride			x			
U217	Thallium nitrate			x			
U218	Thioacetamide		x			x	x
U219	Thiourea		x			x	x
U220	Toluene	x			x	x	x
U221	Toluenediamine		x			x	x
U222	o-Toluidine hydrochloride		x		x	x	x
U223	Toluene diisocyanate		x		x	x	x
U224	Toxaphene		x			x	x
U225	Tribromomethane		x		x	x	x
U226	1,1,1-Trichloroethane		x		x	x	x
U227	1,1,2-Trichloroethane		x		x	x	x
U228	Trichloroethane		x		x	x	x
U229	Trichlorofluoromethane		x		x	x	x
U230	2,4,5-Trichlorophenol		x			x	
U231	2,4,6-Trichlorophenol		x			x	

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

EPA Hazardous Waste Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
U232	2,4,5-Trichlorophenoxyacetic acid		x			x	
U233	2,4,5-Trichlorophenoxypropionic acid alpha, alpha, alpha-Trichlorotoluene		x			x	
U234	Trinitrobenzene		x			x	x
U235	Tris(2,3-dibromopropyl) phosphate		x			x	x
U236	Trypan blue		x			x	x
U237	Uracil mustard		x			x	x
U238	Urethane	x				x	x
U239	Xylene	x			x	x	x
Other hazardous wastes							
Standard Industrial Classification (SIC) Code Number							
2865	Vacuum still bottoms from the production of maleic anhydride	x				x	x
2865	Distillation residues from fractionating tower for recovery of benzene and chlorobenzenes		x			x	
2865	Vacuum distillation residues from purification of 1-chloro-4-nitrobenzene		x			x	x
2865	Still bottoms or heavy ends from methanol recovery in methyl methacrylate production	x				x	x
2869	Heavy ends and distillation from production of carbaryl	x				x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

SIC Code Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
2869	Residues from the production of hexachlorophenol, trichlorophenol and 2,4,5-T		x			x	x
2869	Heavy ends from distillation of ethylene dichloride in vinyl chloride production		x			x	x
2869	Solid waste discharge from ion exchange column in production of acrylonitrile		x			x	x
2869	Bottom stream from quench column in acrylonitrile production of acrylonitrile	x			x	x	x
2869	Still bottoms from aniline production	x				x	x
2869	Tars from manufacture of bicycloheptadiene and cyclopentadiene	x				x	x
2869	Still bottoms from production of furfural	x				x	x
2869	Unrecovered triester from production of disulfoton		x			x	x
2295	Waste polyvinyl chloride (PVC) from the manufacture of coated fabrics		x			x	x
2869	Still bottoms from the production of pentachloronitrobenzene		x			x	
2869	Process clean out sludges from production of 1,1,1-trichloroethane		x			x	x
2869	Heavy ends and light ends from the production of methyl acrylate	x				x	x
2822	Polyvinyl chloride sludge from the manufacture of polyvinyl chloride		x			x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

SIC Code Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
2869	Still bottoms from the purification of fluoromethanes in the production of fluoromethanes		x			x	x
2869	Heavy ends and light ends from the production of ethyl acrylate	x				x	x
2869	Heavy ends from the production of glycerine from allyl chloride	x				x	x
2869	Heavy ends from the distillation of acetic anhydride in the production of acetic anhydride	x				x	x
2869	Light ends from the distillation of acetaldehyde in the production of acetic anhydride	x			x	x	x
	--Reactor cleanup wastes from the chlorination, dehydrochlorination or oxychlorination of aliphatic hydrocarbons		x		x	x	x
	--Fractionation bottoms from the separation of chlorinated aliphatic hydrocarbons		x		x	x	x
	--Distillation bottoms from the separation of chlorinated aliphatic hydrocarbons		x		x	x	x
	--Reactor cleanup wastes from the chlorination or oxychlorination of cyclic aliphatic hydrocarbons		x		x	x	x
	--Fractionation bottoms from the separation of chlorinated cyclic aliphatic hydrocarbons		x		x	x	x
	--Distillation bottoms from the separation of chlorinated cyclic aliphatic hydrocarbons		x		x	x	x
	--Batch residues from the batch production of chlorinated polymers		x			x	x

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

SIC Code Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
	--Solution residues from the production of chlorinated polymers		x		x	x	x
	--Reactor cleanup wastes from the chlorination of aromatic hydrocarbon		x		x	x	
	--Fractionation bottoms from the separation of chlorinated aromatic hydrocarbons		x		x	x	
	--Distillation bottoms from the separation of chlorinated aromatic hydrocarbons		x		x	x	
3333	Zinc production: oxide furnace residue and acid plant sludge			x			
3339	Ferromanganese emissions control: baghouse dusts and scrubwater solids			x			
3339	Ferrochrome silicon furnace emission control dust or sludge			x			
3339	Ferrochrome emissions control: furnace baghouse dust, and ESP			x			
3339	Primary antimony-pyrometallurgical blast furnace slag			x			
3341	Secondary lead, scrubber sludge from SO_2 emission control, soft lead production			x			
3341	Secondary lead-white metal production furnace dust			x			
3341	Secondary copper-pyrometallurgical, blast furnace slag			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

SIC Code Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
3341	Secondary copper-electrolytic refining wastewater treatment sludge			x			
3341	Secondary aluminum dross smelting-high salt slag plant residue			x			
3341	Zinc-cadmium metal reclamation, cadmium plant residue			x			
3691	Lead acid storage battery production wastewater treatment sludges			x			
3691	Lead acid storage battery cleanup wastes from cathode and anode paste production			x			
3691	Nickel cadmium battery production wastewater treatment sludges			x			
3691	Cadmium silver oxide battery production wastewater treatment sludges			x			
3691	Mercury cadmium battery production wastewater treatment sludges			x			
3692	Magnesium carbon battery production chromic acid wastewater treatment sludges			x			
2816	Ash from incinerated still bottoms (paint and pigment production)			x			
2819	Arsenic bearing wastewater treatment sludges from production of boric acid			x			
2834	Arsenic or organo-arsenic containing wastewater treatment sludges from production of veterinary pharmaceuticals			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

SIC Code Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
2851	Wastewater treatment sludges from paint production			x			
2851	Air pollution control sludges from paint production			x			
2869	By-product salts in production of MSMA			x			
2869	By-product salts in production of cacodylic acid			x			
2869	Lead slag from lead alkyl production			x			
3312	Steel Finishing: Alkaline cleaning waste			x			
	--Waste pickle liquor			x			
	--Cyanide-bearing wastes from electrolytic coating			x			
	--Chromate and dichromate wastes from chemical treatment			x			
	--Descaling acid			x			
3322	Lead/phenolic sand-coating waste from malleable iron foundries			x			
3331	Primary copper smelting and refining electric furnace slag, converter dust, acid plant sludge, and reverberatory dust (T)			x			
3332	Primary lead blast furnace dust			x			
3339	Primary antimony-electrolytic sludge			x			
3339	Primary tungsten-digestion residue			x			
1094	Waste rock and overburden from uranium mining			x			
1099	Chlorinator residues and clarifier sludge from zirconium extraction			x			

TABLE 4. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES (con't)

SIC Code Number	Hazardous Waste	Candidate for Incineration			Incineration Type		
		Good	Potential	Poor	Liquid Injection	Rotary Kiln	Fluidized Bed
1475	Overburden and slimes from phosphate surface mining			x			
2874	Waste gypsum from phosphoric acid production			x			
2819- 2874	Slag and fluid bed prills from elemental phosphorous production			x			
2812	Sodium calcium sludge from production of chlorine by Down Cell process			x			
2812	Mercury bearing brine purification muds from mercury cell process in chlorine production			x			
2816	Mercury bearing wastewater treatment sludges from the production of mercuric sulfide pigment			x			
2816	Chromium bearing wastewater treatment sludges from the production of TiO_2 pigment by the chloride process			x			
2816	Arsenic bearing sludges from purification process in the production of antimony oxide			x			
2816	Antimony bearing wastewater treatment sludge from production of antimony oxide			x			
3312	Iron making: Ferromaganese blast furnace dust			x			
	--Ferromanganese blast furnace sludge			x			
	--Electric furnace dust and sludge			x			

Other factors in addition to the criteria used to assign incineration categories to be considered in evaluating wastes for incineration are:

(a) Moisture content,

(b) Potential pollutants present in incinerator effluents,

(c) Inert content,

(d) Heating value (heat of combustion) and auxiliary fuel requirements,

(e) Potential health and environmental effects,

(f) Physical form,

(g) Corrosiveness,

(h) Quantity

(i) Known carcinogenic content,

(j) PCB content.

Once a hazardous waste has been determined to be a good candidate for incineration, the waste must be matched to a particular incineration device. The criteria used for matching different wastes to the various incineration devices are:

(1) Physical form:
  (a) Gas,
  (b) Liquid,
  (c) Slurry,
  (d) Sludge,
  (e) Solid.

(2) Temperature range required for destruction:
  (a) > 2000°F (> 1087°C),
  (b) 1400 - 2000°F (757 - 1087°C),
  (c) 700 - 1400°F (367 - 757°C),
  (d) < 700°F (< 367°C).

(3) Off-gases:

- (a) Essentially oxides of carbon and nitrogen, and water vapor,
- (b) Halogen, sulfur, phosphorus or volatile metal species.

(4) Ash:

- (a) Nonfusible,
- (b) Fusible,
- (c) Metallic.

(5) Heating value (heat of combustion):

- (a) > 10,000 Btu/lb (> 23 MJ/kg),
- (b) 5,000 - 10,000 Btu/lb (12 - 23 MJ/kg),
- (c) < 5,000 Btu/lb (< 12 MJ/kg).

SECTION 3

THERMAL DESTRUCTION DEVICES

A survey of commercial incinerator installations performed by TRW, Inc. (8), showed that the methods of incineration most commonly used are liquid injection incineration, fluidized bed incineration, multiple hearth incineration, rotary kiln incineration, catalytic combustion, molten salt combustion, pyrolysis/starved-air combustion, and wet air oxidation. An excellent review of the state-of-the-art of these incineration processes may be found in a recent publication produced by the Noyes Data Corporation (9). A technical resource document entitled Engineering Handbook for Hazardous Waste Incineration, was prepared for the U.S. Environmental Protection Agency by Monsanto Research Corporation (3). This document provides technical information to be used in the design and performance evaluation of hazardous waste incineration facilities. Topics covered in the handbook include a state-of-the-art survey of incineration and air pollution control design evaluations, overall incineration facility considerations, capital and operating costs, and trial burn summary data. Because rotary kiln and liquid injection are at present the most highly developed and most commonly used incinerators for hazardous waste incineration, primary emphasis has been given in the handbook to these two incineration processes. It is the intent of this chapter to give a brief description of the various commonly used hazardous waste incineration devices. The interested reader is urged to consult the above two references for more detailed information.

Liquid Injection Incineration

Liquid injection incineration can be used to dispose of virtually any combustible liquid waste. A typical liquid injection incineration system is shown in Figure 1. The heart of the system is the waste atomization device or

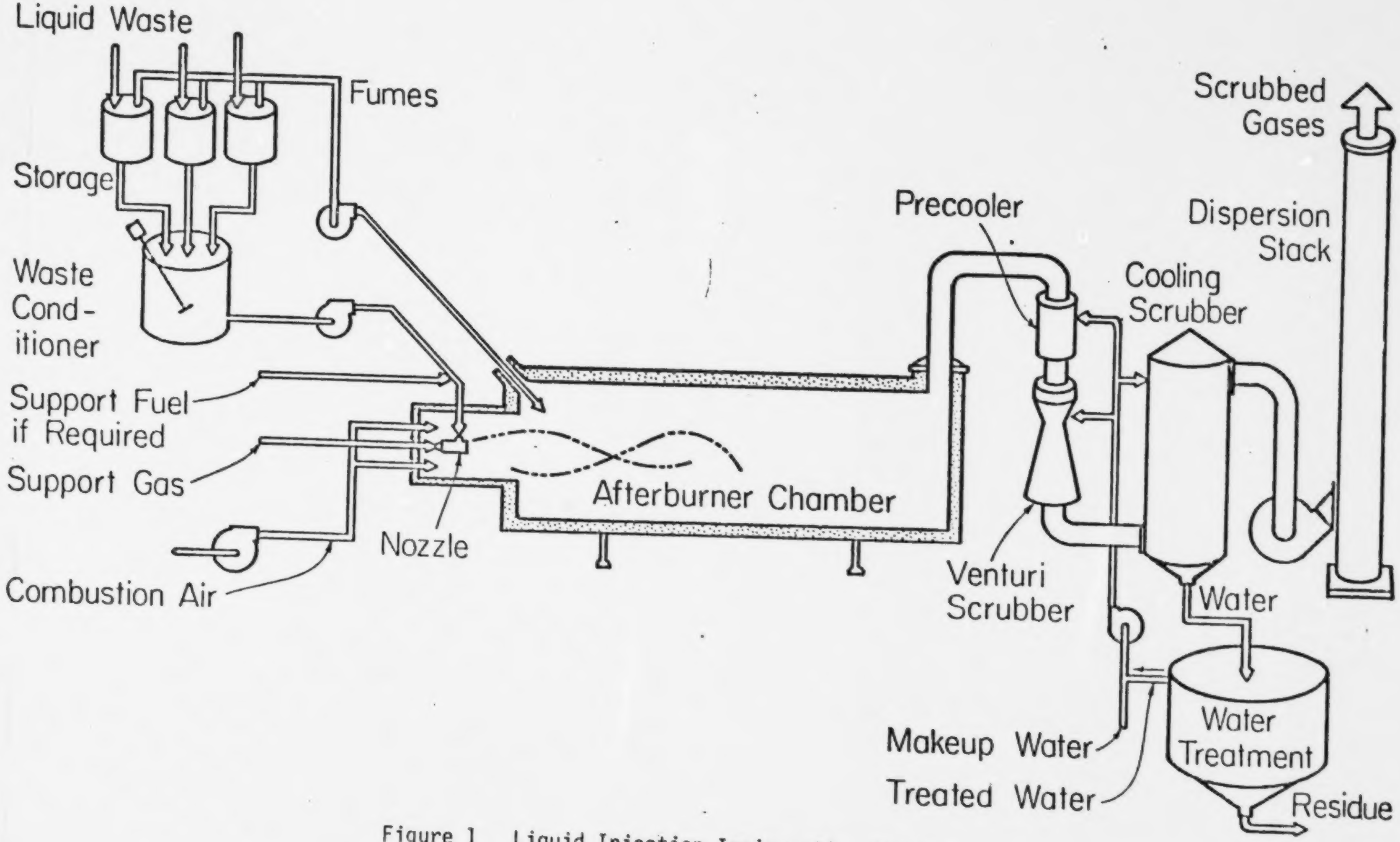
Liquid Waste
Fumes
Storage
Waste Cond-itioner
Support Fuel if Required
Support Gas
Combustion Air
Nozzle
Afterburner Chamber
Precooler
Venturi Scrubber
Cooling Scrubber
Dispersion Stack
Scrubbed Gases
Water
Water Treatment
Residue
Makeup Water
Treated Water

Figure 1 Liquid Injection Incineration System.

nozzle. Because a liquid injection incineration system is essentially a suspension burner, efficient and complete combustion is obtained only if the waste is adequately divided or atomized and mixed with the oxygen source. Atomization is usually achieved either mechanically using rotary cup or pressure atomization systems or via gas fluid nozzles using high-pressure air or steam. For highly viscous materials, some means of lowering viscosity must be used. Common methods employed for this purpose include heating to an appropriate temperature, production of one- or two-phase emulsions, or solubilizing the waste in a lower viscosity liquid. Advantages associated with liquid injection incineration include the following:

(1) Capable of incinerating a wide range of liquid wastes.

(2) No continuous ash removal system is required other than for air pollution control.

(3) Capable of a fairly high turndown ratio (maximum to minimum feed rate operating range).

(4) Fast temperature response to changes in the fuel flow rate.

(5) Virtually no moving parts.

(6) Low maintenance costs.

Potential disadvantages include:

(1) Only wastes that can be atomized through a burner nozzle can be incinerated.

(2) Heat content of waste must maintain adequate ignition and incineration temperatures or a supplemental fuel must be provided.

(3) Burners susceptible to pluggage (burners are designed to accept a certain particle size; therefore, particle size is a critical parameter for successful operation).

(4) Burners may or may not be able to accept a material which dries and cakes as it passes through the atomization nozzles.

The three sources for liquid injection incineration destruction inefficiency are carry-over of unevaporated liquid droplets, carry-over of unreacted vapor due to inadequate temperature exposure, and carry-over of unreacted vapor due to inadequate mixing.

Fluidized Bed Incineration

A typical fluidized bed incinerator is shown schematically in Figure 2. Air driven by a blower enters a plenum at the bottom of the combustor and rises vertically through a distributor plate into a vessel containing a bed of inert granular particles. Sand is typically used as the bed material. The upward flow of air through the sand bed results in a dense turbulent mass which behaves in a way that is similar to that of an airflow through a liquid. Waste material to be incinerated is injected into the bed and combustion occurs within the bubbling bed. Air passage through the bed produces strong agitation of the bed particles. This promotes rapid and relatively uniform mixing of the injected waste material within the bubbling bed.

Advantages associated with fluidized bed incineration include the following:

(1) General applicability for the disposal of combustible solids, liquids, and gaseous wastes.

(2) Simple design concept, requiring no moving parts in the combustion zone.

(3) Compact design due to high heating rate per unit volume (100,000 to 200,000 Btu/hr-ft^3 (900,000 to 1,800,000 kg-cal/hr-m^3)) which results in relatively low capital costs.

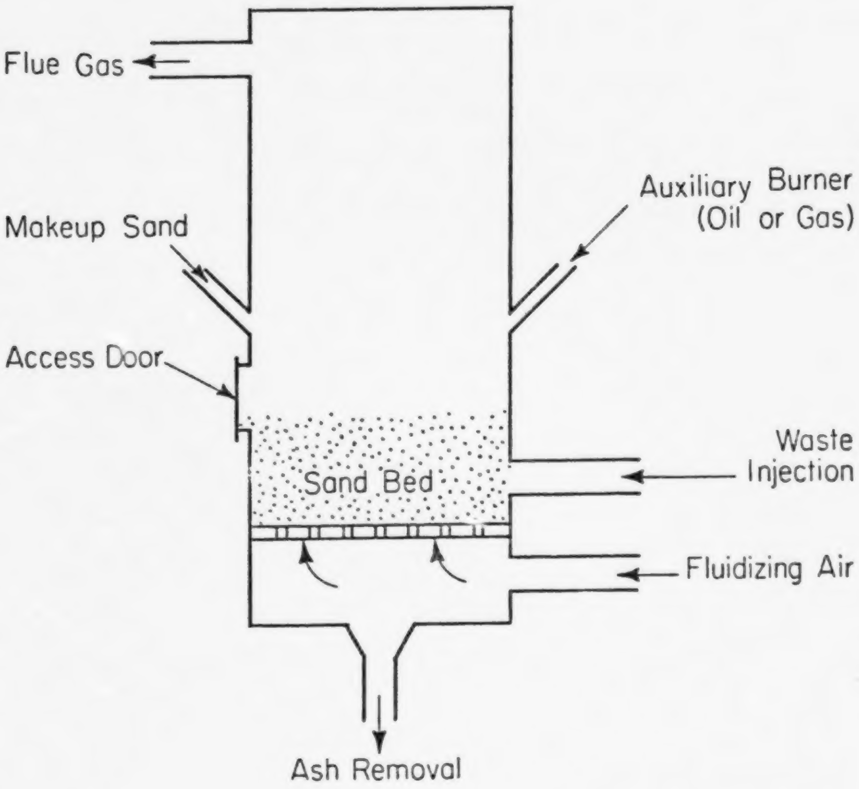
Flue Gas
Auxiliary Burner (Oil or Gas)
Makeup Sand
Access Door
Waste Injection
Sand Bed
Fluidizing Air
Ash Removal

Figure 2 Schematic of a Fluidized Bed Combustor

(4) Relatively low gas temperatures and excess air requirement which tend to minimize nitrogen oxide formation and contribute to smaller, lower cost emission control systems.

(5) Long incinerator life and low maintenance costs.

(6) Large active surface area resulting from fluidizing action enhances the combustion efficiency.

(7) Fluctuation in the feed rate and composition are easily tolerated due to the large quantities of heat stored in the bed.

(8) Provides for rapid drying of high moisture content material, and combustion can take place in the bed.

(9) Proper bed material selection suppresses acid gas formation; hence, reduced emission control requirements.

(10) Provides considerable flexibility for shock load of waste; i.e., large quantities of waste being added to the bed at a single time.

Potential disadvantages include:

(1) Difficult to remove residual materials from the bed.

(2) Requires fluid bed preparation and maintenance.

(3) Feed selection must avoid bed degradation caused by corrosion of or reactions with the bed material.

(4) May require special operating procedures to avoid bed damage.

(5) Operating costs are relatively high, particularly power costs.

(6) Possible operating difficulties with materials high in moisture content.

(7) Formation of low melting point eutectics is a serious problem.

(8) Hazardous waste incineration practices have not been fully developed.

(9) Not well suited for irregular, bulky wastes, tarry solids, or wastes with a fusible ash content.

There are two sources of waste incineration inefficiency associated with fluidized bed incineration: (1) incomplete oxidation of the volatiles and (2) loss of solids which contain unoxidized combustibles. The incomplete oxidation of solids presents the greater difficulty in attaining complete incineration because solids generally require a longer time for complete oxidation than gases at a specific temperature. The loss of incompletely oxidized solids can occur by elutriation or by removal with the bed material. The bed material must be removed and regenerated, continuously or periodically, because of build-up of non-combustibles or attrition of the inert heat carrier. Inadequate residence time of solid wastes is a major cause of inefficiency of fluidized bed incineration.

Multiple Hearth Incineration

Multiple hearth incinerators are particularly well suited for the incineration of solid wastes and sludges. A typical multiple hearth incineration system is shown in Figure 3. Normally, waste material enters the furnace by dropping through a feed port located in the furnace top. Rabble arms and teeth, attached to a vertically positioned center shaft, rotate counterclockwise to spiral the waste across the face of the hearth through alternating drop holes located either along the periphery of the hearth or adjacent to the central shaft. Although the rabble arms and teeth all rotate in the same direction, additional agitation of the waste (back rabbling) is accomplished by reversing the angles of the rabble teeth. Waste retention time is controlled by the design of the rabble tooth pattern and the rotational speed of the central shaft. Ultimately, the residual ash falls to the furnace floor. Air and combustion products flow countercurrently to the feed from the bottom to the top of the combustion chamber. Liquid and/or gaseous combustible wastes may be injected into the unit through auxiliary

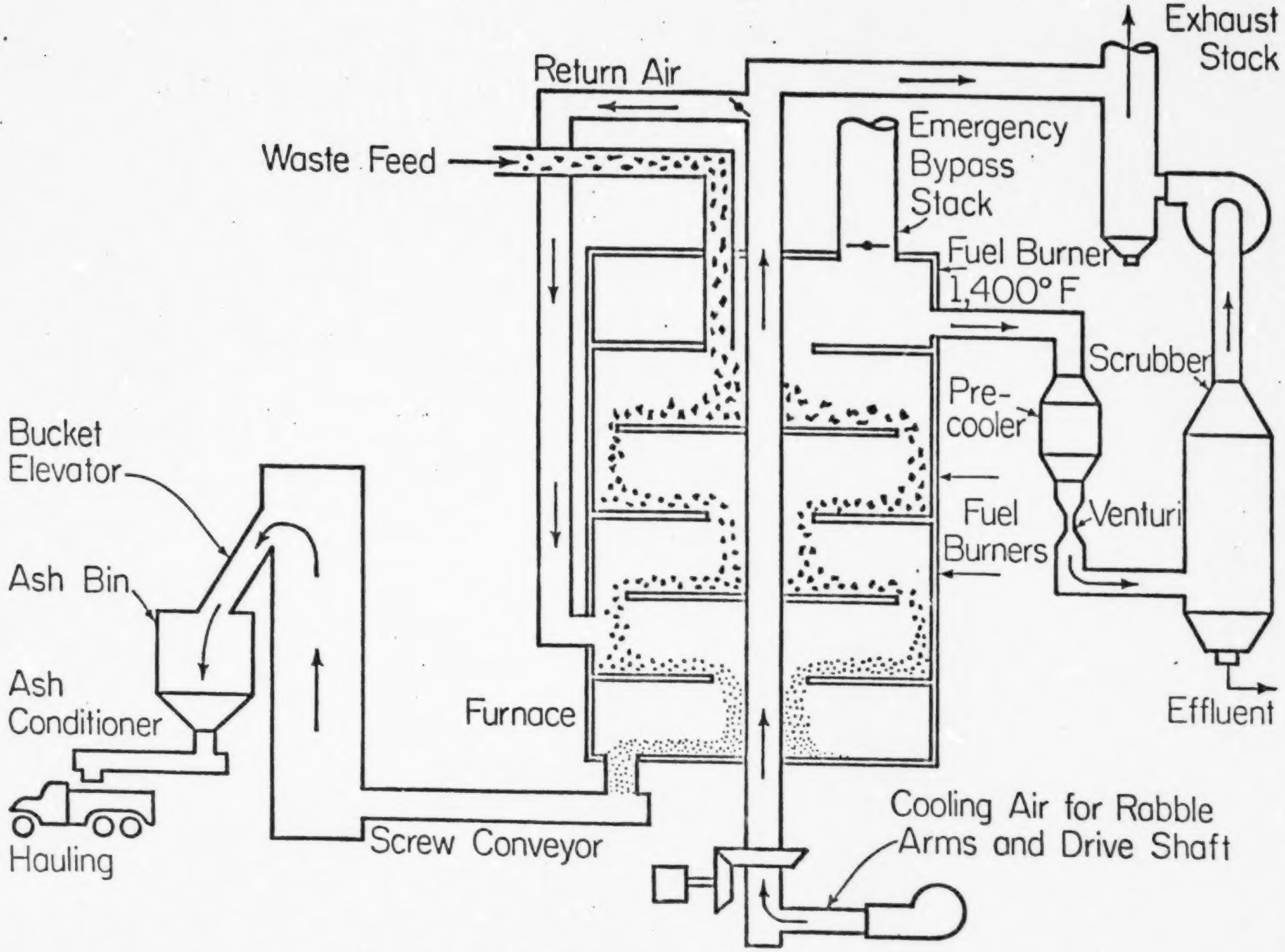
Exhaust Stack
Return Air
Emergency Bypass Stack
Waste Feed
Fuel Burner
1,400° F
Scrubber
Pre-cooler
Bucket Elevator
Fuel Burners
Venturi
Ash Bin
Ash Conditioner
Furnace
Effluent
Cooling Air for Rabble Arms and Drive Shaft
Screw Conveyor
Hauling

Figure 3 Multiple Hearth Incineration System.

burner nozzles. This utilization of liquid and gaseous waste represents an economic advantage as it reduces the quantity of auxiliary fuel required.

Advantages associated with multiple hearth incineration include:

(1) The retention or residence time in multiple hearth incinerators is usually higher for solid material than in other incinerator configurations.

(2) Large quantities of water can be evaporated.

(3) A wide variety of wastes with different chemical and physical properties can be handled.

(4) Multiple hearth incinerators are able to utilize many fuels including natural gas, reformer gas, propane, butane, oil, coal dust, waste oils, and solvents.

(5) Because of its multizone configuration, fuel efficiency is high and typically improves with the number of hearths used.

(6) Fuel burners can be added to any of the hearths to maintain a desired temperature profile.

(7) Multiple hearth incinerators are capable of a turndown ratio of 3:1.

(8) High fuel efficiency is allowed by the multizone configuration.

Potential disadvantages of multiple hearth incineration include:

(1) Due to the longer residence times of the waste materials in multiple hearth incinerators as compared to other incinerator configurations, temperature response throughout the incinerator when the burners are adjusted is usually very slow.

(2) It is difficult to control the firing of supplementary fuels as a result of this slow temperature response.

(3) Maintenance costs are high because of the moving parts (rabble arms, main shaft, etc.) subjected to combustion conditions.

(4) Multiple hearth incinerators are susceptible to thermal shock resulting from frequent feed interruptions and excessive amounts of water in the feed. These conditions can lead to early refractory and hearth failures.

(5) If used to dispose of hazardous wastes, a secondary combustion chamber acting as an afterburner probably will be necessary and different operating temperatures might be necessary to minimize formation of products of incomplete combustion.

(6) Not well suited for wastes containing fusible ash, wastes which require extremely high temperature for destruction, or irregular bulky solids.

Rotary Kiln Incineration

Rotary kiln incinerators are the most versatile of all devices for hazardous waste incineration. The rotary kiln is a long, cylindrical rotating furnace in which solids and slurries are heated by combustion of an auxiliary fuel. The fuel, as well as the solids, can contain hazardous components. The axis of the kiln makes an angle with the horizontal. The feed is introduced at the upper end of the kiln and the hot products of combustion discharged at the lower end. Fuel and air inlets are located either at the lower end, resulting in a countercurrent gas/solids flow, or at the upper end, yielding a cocurrent flow. The rotation of the kiln provides continuous mixing of the solids and continuously renewed contact between solids and the hot walls, as well as direct contact with the hot gases. Exposure to hot gas is often enhanced by the use of hanging chains which break up any solid chunks, mix and stir slurries, and permit wet, sticky material to cling to the chains until dry. Since rotary kilns are normally totally refractory lined and have no exposed metal parts, they can operate at high incineration temperatures and experience low corrosion. A schematic flow diagram for a typical rotary kiln incinerator is shown in Figure 4.

Advantages associated with rotary kiln incineration include:

(1) Will incinerate a wide variety of liquid and solid wastes.

(2) Will incinerate materials passing through a melt phase.

(3) Capable of receiving liquid and solid wastes independently or in combination.

(4) Capable of being fed from drums and bulk containers.

(5) Adaptable to wide variety of feed mechanism designs.

(6) Characterized by high turbulence and air exposure of solid wastes.

(7) Continuous ash removal which does not interfere with the waste oxidation.

(8) No moving parts inside the kiln (except when chains are added).

(9) Adaptable for use with a wet gas scrubbing system.

(10) The retention or residence time of the nonvolatile component can be controlled by adjusting the rotational speed.

(11) The waste can be fed directly into the kiln without any preparation such as preheating, mixing, etc.

(12) Rotary kilns can be operated at temperatures in excess of 2,500°F (1,400°C), making then well suited for the destruction of toxic compounds that are difficult to thermally degrade.

(13) The rotational speed control of the kiln also allows a turndown ratio (maximum to minimum feed rate) of about 2:1.

Potential disadvantages associated with rotary kiln incineration include:

(1) High capital cost for installation.

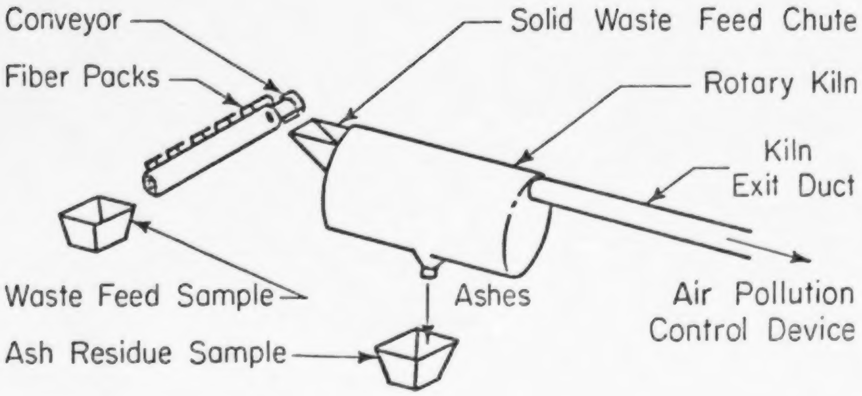
Conveyor
Solid Waste Feed Chute
Fiber Packs
Rotary Kiln
Kiln Exit Duct
Waste Feed Sample
Ashes
Air Pollution Control Device
Ash Residue Sample

Figure 4 Rotary Kiln Incinerator

(2) Operating care necessary to prevent refractory damage; thermal shock is a particularly damaging event.

(3) Airborne particles may be carried out of kiln before complete combustion.

(4) Spherical or cylindrical items may roll through kiln before complete combustion.

(5) The rotary kiln frequently requires additional makeup air due to air leakage via the kiln end seals.

(6) Drying or ignition grates, if used prior to the rotary kiln, can cause problems with melt plugging of grates and grate mechanisms.

(7) High particulate loadings.

(8) Relatively low thermal efficiency.

(9) Problems in maintaining seals at either end of the kiln are a significant operating difficulty.

Catalytic Combustion

Catalytic combustion is an alternative to thermal incineration for oxidizing gaseous combustible contaminants. Their successful operation is limited to a more restricted range of applications than thermal incinerators; but where applicable, catalytic units offer the potentials of significantly lower fuel consumption, and smaller, lighter-weight units. A typical catalytic combustor is shown schematically in Figure 5, and includes a preheat/mixing section, designed to achieve a uniformly preheated and distributed waste stream flow, and the catalyst bed or matrix, in which the major portion of the oxidation reactions take place.

Catalysts in use in catalytic combustors are typically metal mesh-mats, ceramic honeycomb, or other ceramic matrix elements with surface deposits of finely divided platinum or rhenium. Catalytic combustion systems are limited

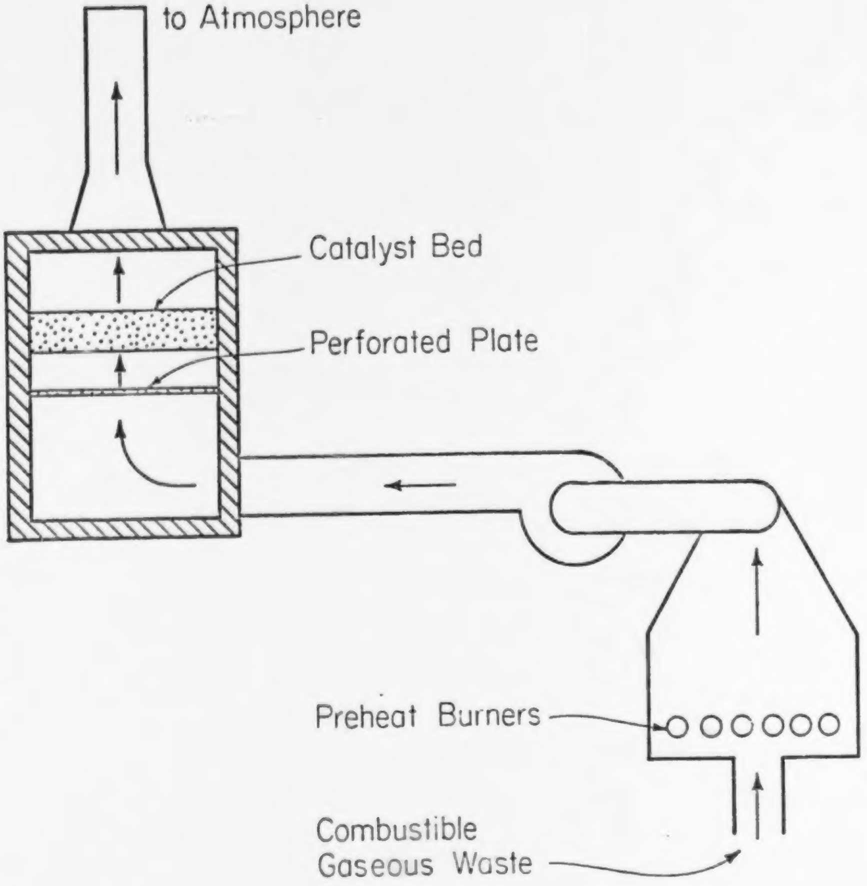
to Atmosphere
Catalyst Bed
Perforated Plate
Preheat Burners
Combustible
Gaseous Waste

Figure 5 Catalytic Combustion System

to applications in which the waste stream has a negligible particulate loading and in which the combustible contaminant is gaseous or can be completely vaporized in the preheat section of the unit. Generally, catalytic incinerators are considered for operation with waste containing hydrocarbon levels that are less than 25 percent of the lower explosive limit. When the waste gas has a sufficient heating value to cause concern about catalyst burnout, the gas may be diluted by atmospheric air to ensure operating temperatures within the operating limits of the catalyst.

In use, the oxidation activity of the catalyst decreases. This decline in activity is accelerated by high temperature exposure, by particulates from the waste stream (e.g., alumina and silica dusts, iron oxides, and some silicons) which coat the catalyst surface, thus inhibiting contact of catalyst and waste stream, and by actual poisoning of the active catalytic sites by specific contaminants in the waste stream (e.g., heavy metals, phosphates, arsenic compounds, and elemental and compounded forms of halogens and sulfur). The performance of a catalytic combustion unit may be maintained as the oxidation activity of the catalyst decreases by initial over-design of the catalyst bed, raising the operating temperature, periodic cleaning of the catalyst, and eventual replacement of the catalyst. Further details concerning catalytic combustion may be found in a report detailing the results of a study performed by Shell Development Company for the U.S. Environmental Protection Agnecy (10).

Molten Salt Combustion

Molten salt incineration (Figure 6) is one of the newest devices for the high temperature thermal destruction of organic wastes. Solid wastes are fed directly to the molten-salt bath, while liquid wastes are sprayed into the combustion air and then fed to the unit. Usually the molten salt bath is

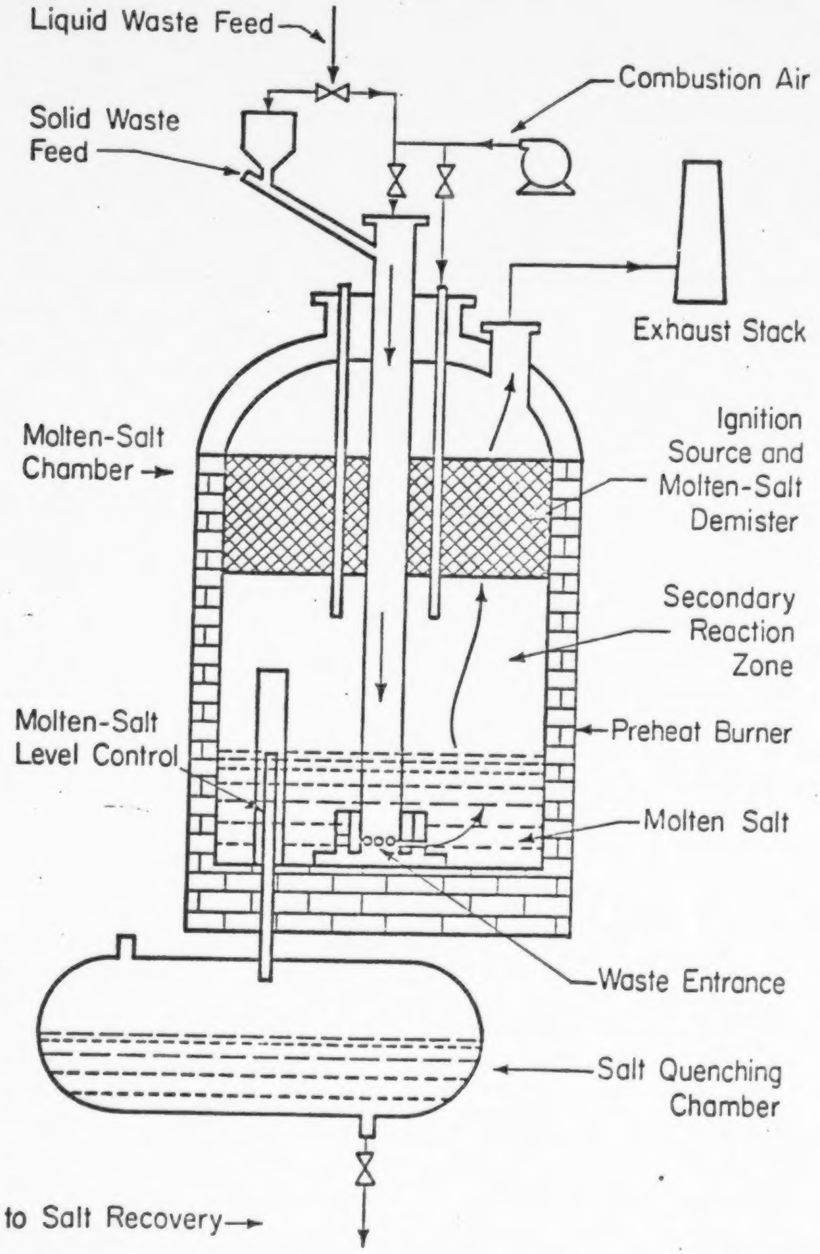
Liquid Waste Feed
Combustion Air
Solid Waste Feed
Exhaust Stack
Molten-Salt Chamber
Ignition Source and Molten-Salt Demister
Secondary Reaction Zone
Molten-Salt Level Control
Preheat Burner
Molten Salt
Waste Entrance
Salt Quenching Chamber
to Salt Recovery

Figure 6 Molten Salt Combustion System.

composed of approximately 90 percent sodium carbonate and 10 percent sodium sulfate. Substitution of other salts such as potassium carbonate may be used for lower incineration temperature requirements. The use of reactive salts, such as the eutectic mixtures NaOH - KOH and Li_2CO_3 - Na_2CO_3 - K_2CO_3, produces the additional benefit of entrapping potentially toxic or objectionable off-gas constituents such as heavy metals (mercury, lead, cadmium, arsenic, selenium). This reduces or eliminates the need for pollution-abatement equipment. The spent salt often can be regenerated or may be land-disposed. Start up and support fuels include gas, oil, and coal.

Pyrolysis/Starved-air Combustion

Pyrolysis may be defined as the gasification and/or liquefaction of combustible elements by heat in the total absence of oxygen. Starved-air combustion is a combustion process occurring with air levels less than the stoichiometric requirement for combustion. In either process, waste organic compounds are distilled or vaporized to form char, gas, and liquid organics. These resulting substances may be of lower molecular weight than the original substance due to thermal fission or may be of increased molecular weight depending on the operating conditions. Heat for the process maybe provided by the combustion of part of the volatile products, by combustion of the char or by combustion of auxiliary fuel. The unoxidized portion of the combustible gas may be used as fuel in an external combustion chamber with the resulting energy recovered by conventional waste-heat-boiler technology. Khodadadi (11) has reviewed the subject of pyrolysis/starved air combustion and the reader is referred to his thesis for further information.

Wet Air Oxidation

Wet air oxidation is ideally suited to the oxidation waste liquors, slurries, and sludges which are too dilute to incinerate by dry combustion and too refractory to handle by chemical or biological oxidation. This process relies on conditions of elevated temperature and pressure to oxidize organic substances in aqueous solution. Temperature is the most important process parameter (12). Pressure is required to maintain water in the liquid state and to provide a minimum overpressure of oxygen. A typical wet air oxidation system is shown in Figure 7. The process works on the principle that the rate of oxidation of organic compounds is significantly increased at higher pressures. Thus, by pressurizing an aqueous organic waste, heating it to an appropriate temperature and then introducing atmospheric oxygen, an incomplete liquid-phase oxidation reaction is produced which destroys most of the organic compounds. The process exhibits varying levels of combustion efficiency, depending upon the characteristics of the waste. Wet air oxidation is often used as a pretreatment step to destroy toxic compounds before conventional biological wastewater treatment (13).

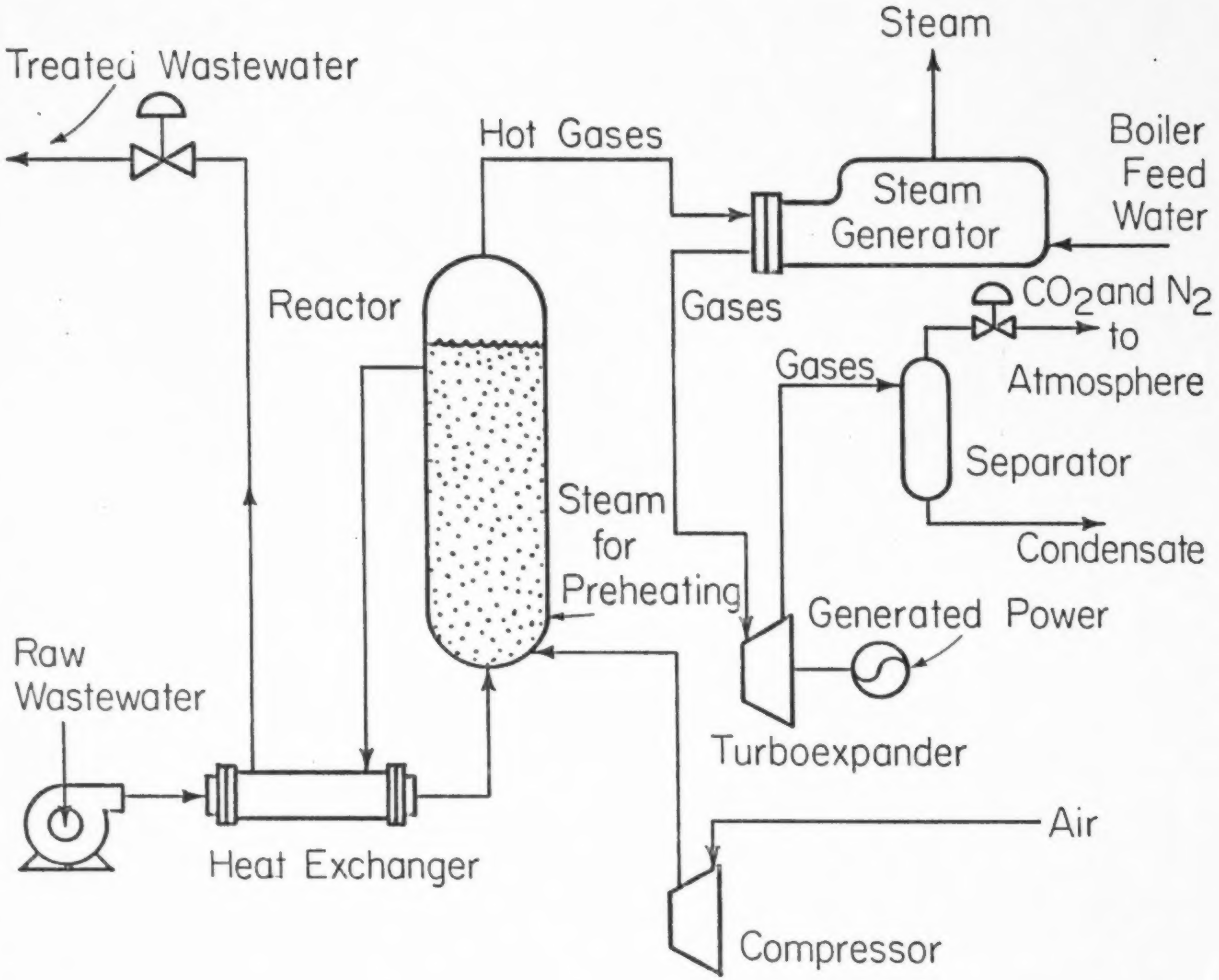
Treated Wastewater
Hot Gases
Steam
Boiler
Feed
Water
Steam
Generator
Reactor
Gases
CO_2 and N_2
to
Atmosphere
Gases
Separator
Steam
for
Preheating
Condensate
Generated Power
Raw
Wastewater
Turboexpander
Air
Heat Exchanger
Compressor

Figure 7 Wet Air Oxidation System

SECTION 4

COMMERCIAL SCALE HAZARDOUS WASTE THERMAL DESTRUCTION TESTS

In order to provide a broad assessment of the capabilities of commercially available thermal destruction units, the U. S. Environmental Protection Agency awarded a two-phase contract to the team of TRW Defense and Space Systems Group and Arthur D. Little, Inc. The first phase was the development of an operational plan for selecting chemical wastes and thermal destruction units that could be tested for their capabilities to destroy chemical wastes containing hazardous components. This encompassed the following tasks:

(1) Classification, identification, prioritization and selection of wastes which provided a reasonable cross-section of currently generated industrial wastes with particular attention to quantities and hazardous properties of the waste.

(2) Selection of units chosen to be representative of the most advanced engineering methods of thermal destruction.

(3) Assignment of top priority wastes to specific units on the basis that the wastes could be expected to be destroyed effectively, the transportation and handling of the wastes would be feasible, and all units would be tested with at least one priority waste.

The second phase of the project used the results from the first phase and encompassed the following tasks:

(1) Development of a testing and analytical protocol and outfitting a mobile laboratory for field testing.

(2) Obtaining wastes from generating sources and arranging for shipment to the thermal destruction units.

(3) Contracting with the operators of thermal destruction facilities for the tests.

(4) Preparing a detailed test and analytical program for each facility and carrying out the program at the thermal destruction facility.

(5) Analyzing samples in the mobile laboratory and interpreting data.

(6) Preparing a report on each unit tested.

Two criteria were developed with which to prioritize candidate waste materials. These were:

(1) Hazard Rating (r_{max}) - A given compound or waste may have a number of properties for which it is considered hazardous (flammability, oral toxicity, inhalation toxicity, carcinogenicity, etc). For each hazardous property, four ratings were established with assigned values of 1, 10, 100, 1,000--the higher the rating, the more hazardous the waste. In assigning a hazard rating to an individual waste with several hazardous properties, the highest hazard rating was used irrespective of which hazardous property the rating represented.

(2) Quantity Rating (Q) - Four ranges of waste generation volume were chosen. The ranges selected were over 45,400 metric tons per year, 4,540 to 45,400 metric tons per year, 454 to 4,540 metric tons per year and less than 454 metric tons per year. These volume ranges were assigned ratings of 1,000, 100, 10, and 1, respectively.

After hazard and quantity ratings were assigned to a waste, the priority category was determined by multipying the two ratings together. A total of 50 wastes were selected and ranked as prime candidates for consideration for the thermal destruction tests. The distribution among priority categories for these 50 wastes is shown in Table 5.

A brief description of the wastes finally chosen for the actual thermal destruction tests is given in Table 6. Table 7 provides a brief description

TABLE 5. DISTRIBUTION OF 50 SELECTED WASTES BETWEEN PRIORITY CATEGORIES (14)

Priority Category	$Q \times r_{max}$	Number of Waste Streams in Category
I	10^6	1
II	10^5	2
III	10^4	3
IV	10^3	18
V	10^2	13
VI	10	8
VII	1	5
	Total	50

TABLE 6. BRIEF DESCRIPTIONS OF THE WASTES DESTROYED IN PHASE II TESTS (14)

Waste	Physical Characteristics of Waste	Chemical Composition of Waste	Waste Characteristics as Described by the Waste Generator
Liquid Injection - The Marquardt Co.			
Ethylene waste	Liquid, low viscosity 10,000 kcal/kg (18,000 Btu/lb)	89% C; 9% H; 1.3% S Unsaturated and aromatic hydrocarbons <0.01% Ash, metals <1ppm	Water separable oil containing heavy polymeric oils with traces of aromatics. Liquid >5000 kcal/kg (>10,000 Btu/lb)
Hexachlorocyclopentadiene waste	Liquid, moderate viscosity Suspensed, waxy particulate 2400 kcal/kg (4000 Btu/lb) Miscible with No. 2 fuel oil	77% Cl; 21% C; <1% H, N, S Mainly C_5Cl_6 and C_5Cl_8 0.04% Ash. Fe, Si, Al, Na Ca at 10-100 ppm	Mixture of chlorinated toluenes, pentanes, and benzenes. Liquid >2800 kcal/kg (>5000 Btu/lb)
Pyrolysis-Surface Combustion Div. Midland Ross Corp.			
API separator bottoms	Sludge: 70% water 1390 kcal/kg (2500 Btu/lb)	85% C; 12% H; 1.2% S; <1% N Unsaturated and aromatic hydrocarbons ~10% Ash. Zn, Cr, F, Pb at 200-1000 ppm.	No description provided
Styrene waste	Liquid, moderate viscosity suspended particulate 8900 kcal/kg (16,000 Btu/lb)	85% C; 8% S; 7% H; < 1% N Aromatic hydrocarbons. Elemental sulfur <1% Ash; Zn, Cr, Pb at 0.1-2 ppm.	Polymeric tar containing styrene and ethyl benzene tar. >2800 kcal/kg (>5000 Btu/lb)
Rubber waste	Solid, 30% water 5500 kcal/kg (9800 Btu/lb)	80%C; 10% H; <1% S, N Polymeric unsaturated and aromatic hydrocarbons 1-5% Ash; Cr, Pb, Zn, F at 20-150 ppm.	Solid waste containing 58% rubber, and carbon black plus the usual salts, fatty acids, soaps, etc. Solids >2800 kcal/kg (>5000 Btu/lb)
Fluidized Bed Combustion-Systems Technology, Inc.			
Methyl methacrylate waste	Liquid, low viscosity, 38% water. Gritty sediment <1500 kcal/kg (<2700 Btu/lb)	38% C; 9% H; <1% Cl, N, S methyl methacrylate (34%) and other oxygenated organics 2% Ash. Na, S, Ti, Al, Ca, Pb, Si, Mg, P at 50-300 ppm.	No description provided
Phenol waste	Sludge, 86% water <1500 kcal/kg (<2700 Btu/lb)	10.5% H; 6% C; <1% N, S, Cl Phenols and Cresols 5.5% Ash. S, Na, Fe, Ca, Si, Al, K, Mg, and P at >25 ppm	No description provided
Wet Air Oxidation-Zimpro			
Coke plant waste	Aqueous solution Dissolved solids <1% Small amt. particulate <55 kcal/kg (100 Btu/lb)	Phenol and cresol, 800 ppm Amines, 25-50 ppm. COD, 5520 ppm NH_3, Cl^-, SO_4 at 2500-3500 ppm CN^-, 310 ppm; pH 9	No description provided
Amiben® waste	Aqueous solution Dissolved solids 6-7% <55 kcal/kg (100 Btu/lb)	Dichloronitrobenzoic acid, 20 g/l; COD, 30 g/l, Cl^-, 6 g/l; pH 12, Sodium, 5%	No description provided
Rotary Kiln Incineration -3M			
Polyvinyl chloride (PVC)	Sludge, 72% water 26% solids 740 kcal/kg (1300 Btu/lb)	Vinyl chloride monomer, 220 ppm Solids - polyvinyl chloride 2% Ash; Low metals	PVC resins containing 100 to 300 ppm vinyl chloride monomer. Solid. >5000 kcal/kg (>10,000 Btu/lb)
Liquid Injection-Rollins			
Nitrochlorobenzene waste	Liquid, moderately viscous Variable amounts of crystalline particulate 5050 kcal/kg (9100 Btu/lb)	46% C; 23% Cl; 9% N, 3% H Nitrochlorobenzene (95%) <1% Ash; mainly Ca,Fe,Mg. 200 ppm S	Heavy ends and tars from ortho-chloronitrobenzene vacuum distillation. Tar. >2800 kcal/kg (>5000 Btu/lb)
Rotary Kiln-Rollins			
PCB waste capicitors	1. Whole capacitors	Presumably same as shredded waste below.	Waste containing PCBs and alpha methylstyrene in capacitors. Solid
	2. Hammermilled capacitors; Oily shredded paper and metal	29% organics, mostly PCBs; 32% paper and plastics; 39% ash	<2800 kcal/kg (<5000 Btu/lb)

TABLE 7. BRIEF DESCRIPTIONS OF THE FACILITIES TESTED (14)

Facility Tested	Facility Type	Comments and Constraints on Suitable Wastes	Wastes Tested
The Marquardt Company Van Nuys, Ca.	Liquid injection (With wet scrubber)	*200-240 l/hr (50-60 gallons/hr) *1.4×10^6 kcal/hr (5.5×10^6 Btu/hr) *Temperatures up to 1650°C (3000°F) *Liquid waste with low particulate only	Ethylene waste Hexachlorocyclopentadiene (C-5,6) waste
Surface Combustion Div., Midland Ross Corp. Toledo, Ohio	Pyrolysis (With rich fume incinerator)	*90-180 kg/hr (200-400 lb/hr) *0.5×10^6 kcal/hr (2×10^6 Btu/hr) *Temperatures up to 760°C (1400°F) *Solids, sludges, tars *Resource (heat) recovery potential	Centrifuged API separator bottoms Styrene tars Rubber manufacturing wastes
Systems Technology, Inc. Franklin, Ohio	Fluidized bed (With wet scrubber)	*Up to 1360 l/hr (340 gal/hr) *15×10^6 kcal/hr (59×10^6 Btu/hr) *Temperatures 600-810°C (1100-1500°F) *Liquids, slurries, powders	Methyl methacrylate waste Phenol waste
Zimpro, Inc. Rothschild, Wis.	Wet air oxidation	*20-400 l/hr (5-100 gal/hr) *Temperatures 230-325°C (450-620°F) *Pressure up to 1.1 $\times 10^4$ Kilopascals (1600 psig) *Aqueous solutions	Coke plant waste Amiben® manufacturing waste
3M Chemolite Incinerator System Cottage Grove, Minn.	Rotary kiln (with wet scrubber)	*1.8×10^3 kg/hr (4000 lb/hr) *22.7×10^6 kcal/hr (90×10^6 Btu/hr) *Temperatures 980-1090°C (1800-2000°F) *Pumpable liquids and drummed wastes	Polyvinyl chloride waste
Rollins Environmental Services, Inc. Deer Park, Texas	Rotary kiln and liquid injection incinerator (with wet scrubber)	*28×10^6 kcal/hr (110×10^6 Btu/hr) *Temperatures 1300-1500°C (2400-2700°F) *Pumpable liquids and drummed wastes	Kiln: Discarded capacitors containing PCB's (polychlorinated biphenyls) Liquid injection: Nitrochlorobenzene waste

of the commercial facilities in which the thermal destruction tests were performed. In addition to the wastes and facilities given in Tables 6 and 7, a mixture of chlorinated hydrocarbon and PCB wastes was tested in the St. Lawrence Cement Company wet process kiln. The purpose of these cement kiln tests was to determine whether chlorinated organic wastes could be burned in a cement kiln without adverse effects on either the environment or the cement that is produced. It is currently common practice to add chlorides to some cement kilns in order to reduce the alkali content of the cement that is produced. By burning chlorinated hydrocarbons, both the chlorine and energy are recovered from the waste, thus reducing the cement plant's need for chlorides and fuel oil. Operating conditions for the thermal destruction tests performed are given in Table 8.

Analyses of feed and effluent samples were designed to provide two types of information. One objective was to identify potentially hazardous components of the waste feed and search for those particular species in effluent samples. A second analytical strategy was to apply survey-type techniques to the effluent samples to detect other species of potential concern such as partial combustion products and heavy metals. The primary criterion for evaluating facility effectiveness was the amount of undegraded and/or partially degraded waste material that could be found in the effluent from the reaction zone of the thermal destruction facility. Calculated values of destruction efficiency obtained from the results of this test program are summarized in Table 9.

For liquid injection incineration of the ethylene waste, no known toxic species were identified in the combustor effluent at levels that would require control technology. Sulfur dioxide was present at 100 to 200 ppm. For the hexachlorocyclopentadiene waste tested at the same facility, no known toxic

TABLE 8. OPERATING CONDITIONS FOR WASTE DESTRUCTION (14)

Waste	Incinerator	Temperature	Residence Time
Ethylene Waste	Liquid Injection	1349° to 1752°C	0.14 to 0.19 sec
Hexachlorocyclopentadiene Waste	Liquid Injection	1348° to 1378°C	0.17 to 0.18 sec
API Waste	Pryolysis	760°C	12.5 min
Styrene Waste	Pryolysis	650° to 760°C	12.5 min
Rubber Waste	Pryolysis	760°C	15 min
Phenol Waste	Fluidized Bed	740° to 757°C	12 to 14 sec
Methyl methacrylate Waste	Fluidized Bed	774° to 788°C	12 sec
Coke Plant Waste	Wet air oxidation	279°C at 107 atm	1.15 hr
Amiben® Waste	Wet air oxidation	281°C at 107 atm	1 hr
PVC Waste	Rotary Kiln	870°C in primary combustion zone 980°-1090°C in secondary combustion zone	2 to 3 sec
Hammermilled PCB Waste	Rotary Kiln	1252°C in kiln, 1331°C in afterburner	3.2 sec
Whole PCB waste	Rotary Kiln	1339°C in kiln, 1332°C in afterburner	3.08 sec
Nitrochlorobenzene Waste	Liquid Injection	1307° to 1332°C	2.3 sec
Chlorinated Hydrocarbon and PCB Wastes	Cement Kiln	Not reported	5 to 10 sec

TABLE 9. DESTRUCTION EFFICIENCES CALCULATED FROM PHASE II TEST RESULTS (14)

Waste	Type of Facility	Destruction Efficiency (%)
Ethylene	Liquid Injection	> 99.999
Hexachlorocylopentadiene	Liquid Injection	> 99.999
Nitrochlorobenzene	Liquid Injection	> 99.999
Chlorinated Aromatics	Cement Kiln	≥ 99.989*
Polychlorinated Biphenyls	Cement Kiln	≥ 99.986*
Phenol	Fluidized Bed	> 99.999
Methyl Methacrylate	Fluidized Bed	> 99.999
Coke Plant	Wet Air Oxidation	90
Amiben®	Wet Air Oxidation	90
Polyvinyl Chloride	Rotary Kiln	≥ 99.996
PCB's in Capacitors (Hammermilled)	Rotary Kiln	> 99.999

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*Based on stack emissions, not combustion zone data.

organics were found. The hydrochloric acid emissions do require control. Other inorganics were lead, cobalt, chromium, and manganese at concentrations ranging from 0.1 to 1.5 mg/m^3.

For pyrolysis of both API waste and rubber waste, the pyrolyzer gas effluent had a composition similar to that obtained from coking or gasification of coal. High levels of polynuclear aromatics (350 to 490 mg/m^3) and other condensable organics (> 1% by volume) require a close-coupled, carefully designed heat recovery system. Sulfur gases were present at < 200 mg/m^3 as S; lead and zinc were found for API waste only. Pyrolysis gas from styrene tests had a composition quite similar to the feed but with more polynuclear aromatics; substantial quantities of soot were also formed.

Fluidized bed combustion of methyl methacrylate waste produced no known toxic organics in the combustor effluent. Lead was found at about 1 mg/m^3. A very similar composition was found for combustion of phenol at the same facility, except that lead levels were as high as 5 mg/m^3

The aqueous effluents from wet air oxidation of coke plant waste and Amiben® waste contained residual organic material. For coke plant waste, identifed species were phenol (1 mg/l) and quinoline (13 mg/l); Chemical Oxygen Demand (COD) was 500 mg/l. These levels are probably acceptable for discharge to wastewater treatment plant. For Amiben® waste, dinitrochlorobenzene at 2 g/l would require removal in a separate operation following wet air oxidation. Total COD for that effluent was 3 g/l. Total volatile hydrocarbons in the vent gas were 180 ppm and 750 ppm for coke plant waste and Ambien® waste, respectively.

Rotary kiln incineration both of PVC waste and No. 2 fuel oil (background test) at the 3M Company facility produced polynuclear aromatic hydrocarbons at 2 to 5 mg/m^3 in the hot zone effluent. Hydrochloric acid emissions were about

1.5 g/m^3 and would, of course, require control. Rotary kiln incineration of both whole and hammermilled PCB-containing capacitors did not lead to detectable amounts of toxic organic species in the gaseous combustor effluent. Hydrochloric acid emissions were in the 450 to 700 ppm range. Potentially hazardous metals found were 11 to 12 mg/m^3 of lead and 1 to 2.6 mg/m^3 of tin.

Destruction of nitrochlorobenzene waste in a liquid injection incinerator (Rollins) did not result in formation of detectable quantities of organic materials known to be hazardous. Hydrochloric acid emissions from the combustor were 2.5 to 6 g/m^3 and would certainly require emission control.

SECTION 5

LABORATORY SCALE THERMAL DESTRUCTION TESTS

When individual toxic organic substances or multicomponent industrial organic wastes are subjected to some form of thermal destruction technique, that technique may be quite successful in bringing about the destruction of the parent molecule. However, although the parent molecule may be dealt with at certain thermal exposures, other secondary or intermediate reaction products may be produced that are more toxic or more thermally stable than the parent substance. Thus, in order to determine the thermal requirements necessary for environmentally acceptable disposal of hazardous materials, it is essential that fundamental thermal decompositon data for these toxic substances be obtained.

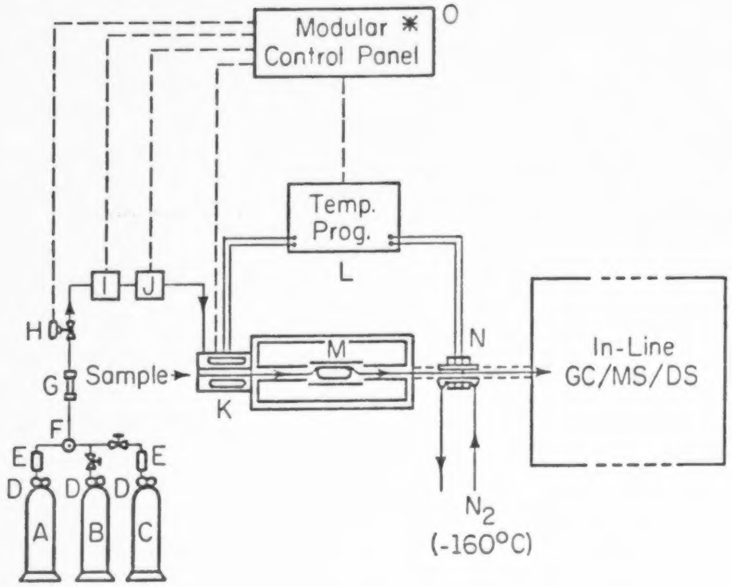
There are several advantages to generating fundamental thermal decomposition data in the laboratory. First, thermal decomposition experiments can be conducted much more safely in a properly equipped laboratory than in larger throughput units. Second, data generated in the laboratory can be much more precise and comprehensive than thermal decomposition data generated in field-scale studies. Third, laboratory thermal decomposition data can be obtained economically and in a short period of time.

Once the thermal decompositon properties of a particular material have been characterized in the laboratory, the preliminary decision can be made as to whether high-temperature incineration is a viable disposal route for that particular material. If no adverse characteristics are detected during the laboratory experiments, then the material may be subjected to larger-scale thermal decomposition studies. However, if the laboratory data indicate difficulties or problem areas, then thermal decomposition is probably not a viable disposal method for that particular substance.

Laboratory-scale thermal decompositon studies of various organic materials are being performed at the University of Dayton Research Institute. These experiments are being performed using recently developed second generation thermal decompositon instrumentation (15-17). The present instrumentation is referred to as a thermal decomposition analytical system (TDAS). This system incorporates a versatile in-line thermal decomposition unit with sophisticated analytical instrumentation capable of analyzing the various decomposition products.

The TDAS is designed to evaluate the thermochemical behavior of volatile materials under controlled conditions. As indicated in Figure 8, it consists of a modular control panel (where the operating parameters for tests are established), several gas cylinders (that supply reaction atmospheres with known compositions), a sample insertion and vaporization chamber, a special quartz tube reactor in a furnace (for the decomposition of samples), a product collection trap, a gas chromatograph, a mass spectrometer, and a mini-computer. Figure 9 is a block diagram showing a simplified representation of the operational relationships of the various components.

In operation, several micrograms of a solid sample (or several microliters of a liquid or gaseous sample) are introduced into a sample injection chamber (location K in Figure 8). The chamber is then sealed and flushed with the controlled atmosphere to be used for the experiment. Solid and liquid samples are heated, vaporized at temperatures up to 300°C (over a controlled time interval), and mixed with a continuous stream of the reaction atmosphere. Samples may be flash pyrolyzed or gradually vaporized, depending on the desired reaction conditions. The mixture then passes through a reactor (location M) consisting of a 98 cm long, 0.097 mm inside diameter, thin walled, helical quartz tube enclosed in an electric furnace. The furnace and


Modular * Control Panel
O
Temp. Prog.
L
I
J
H
G
Sample
F
E
E
D
D
D
A
B
C
K
M
N
In-Line GC/MS/DS
N_2 (-160°C)

A	Helium Gas	I	Flow Transducer
B	Compressed Air	J	Pressure Transducer
C	Inert Carrier	K	Insertion Chamber
D	Pressure Regulator	L	Temperature Programmer
E	Oxygen Scrubber	M	Reactor in Furnace
F	Directional Valve	N	Product Collection Trap
G	Filter	O	Modular Control Panel
H	Flow Control Valve		

* The Modular Control Panel did not Appear in the Original Publication

Figure 8 Simplified Schematic of TDAS (3)

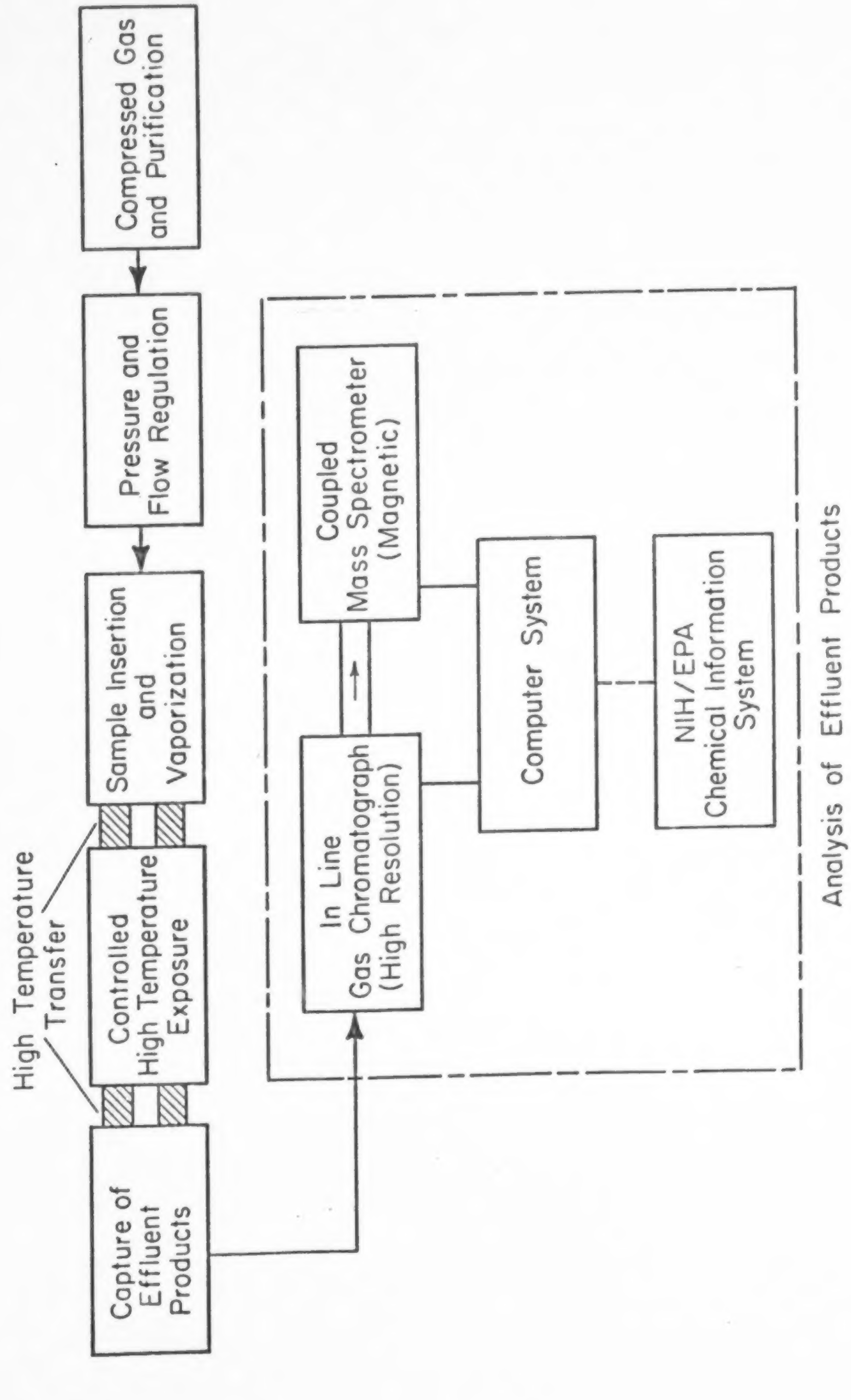

Compressed Gas and Purification
Pressure and Flow Regulation
Sample Insertion and Vaporization
High Temperature Transfer
Controlled High Temperature Exposure
Capture of Effluent Products
In Line Gas Chromatograph (High Resolution)
Coupled Mass Spectrometer (Magnetic)
Computer System
NIH/EPA Chemical Information System
Analysis of Effluent Products

Figure 9 Block Diagram of TDAS (3)

tube can be operated at temperatures up to 1150°C (±2°). The temperature of the reactor is monitored by a thermocouple located at a point representing the mean temperature for the reactor furnace.

It is estimated that a typical reaction mixture entering the TDAS reactor heats to the reactor temperature within 0.005 seconds. Ninety-five percent of the molecules are estimated to be exposed to the reported temperature over time intervals with a maximum deviation of 4 to 10 percent from the reported mean residence time, depending on the conditions of the test (3). The percent deviation increases as the mean residence time decreases. The temperature is controlled to within ±2°C across the operating range of the device. Mean residence times between 0.25 and 5.0 seconds may be selected. It is possible to operate the reactor at pressures up to 2 atmospheres.

The effluent from the TDAS reactor enters a sorbent trap (location N) that can be maintained at -110°C. In the trap, reactions are quenched and reaction products and unreacted sample are collected with a sorbent. The chemicals collected are than thermally desorbed directly into a capillary column gas chromatograph/mass spectrometer for identification and quantification of reaction products and unreacted sample.

The chromatograph has been used with glass and fused silica capillaries coated with selected materials. The mass spectrometer contains a total ion detector upstream of the magnetic sector. This detector may be calibrated and used to measure quantities of pure substances leaving the mass chromotograph at different times. A photomultiplier tube downstream of the magnetic sector of the mass spectrometer responds to the ionic fragments of molecules emerging from the magnetic field. The identity of chemicals and mixtures of chemicals emerging from the gas chromotograph can be determined by comparing observed ion fragment patterns with those of known compounds. The NIH/EPA Chemical

Information Mass Spectral Data Base is routinely used to help identify compounds and mixtures.

Information that can be and has been obtained using the TDAS include: (1) the effects of oxygen level on thermal decomposition profiles; (2) the effect of residence time on thermal decomposition profiles; (3) identification of thermal decomposition products; (4) determination of specific rate constants and the order of reaction; and (5) determination of activation energy and thermodynamic parameters. Thermal decomposition tests performed with the TDAS include work done with polychlorinated biphenyls (PCB's), "Hex" wastes (see page 87 for description), polybrominated biphenyls (PBB's), and Kepone.

PCB thermal decomposition experiments were conducted with 2,2',5,5'-tetrachlorobiphenyl, 2,2',4,5,5' - pentachlorobiphenyl, and 2,2',4,4',5,5' - hexachlorobiphenyl. Thermal decompositions profiles for these isomers in a flowing air environment with a 2.0 second residence time at the exposure temperature are depicted in Figure 10. The major decomposition products formed by the thermal stressing of the isomers at 725°C in flowing air for two seconds residence time are itemized in Table 10. The chlorinated aromatics which were formed from the decomposition of 2,2',4,4',5,5'-hexachlorobiphenyl are shown in Figure 11. These were formed in large quantities approaching 1 percent by weight. The formation of these chlorinated aromatics is alarming, not only from the toxicity standpoint, but from the fact that their thermal stability is such that they remain intact, even after the parent PCB has been destroyed. Experiments to determine the effects of different flowing gaseous atmospheres were performed with the 2,2',4,5,5'-pentachlorobiphenyl. The results are shown in Figure 12. Differences noted between air (≈ 21% O_2)

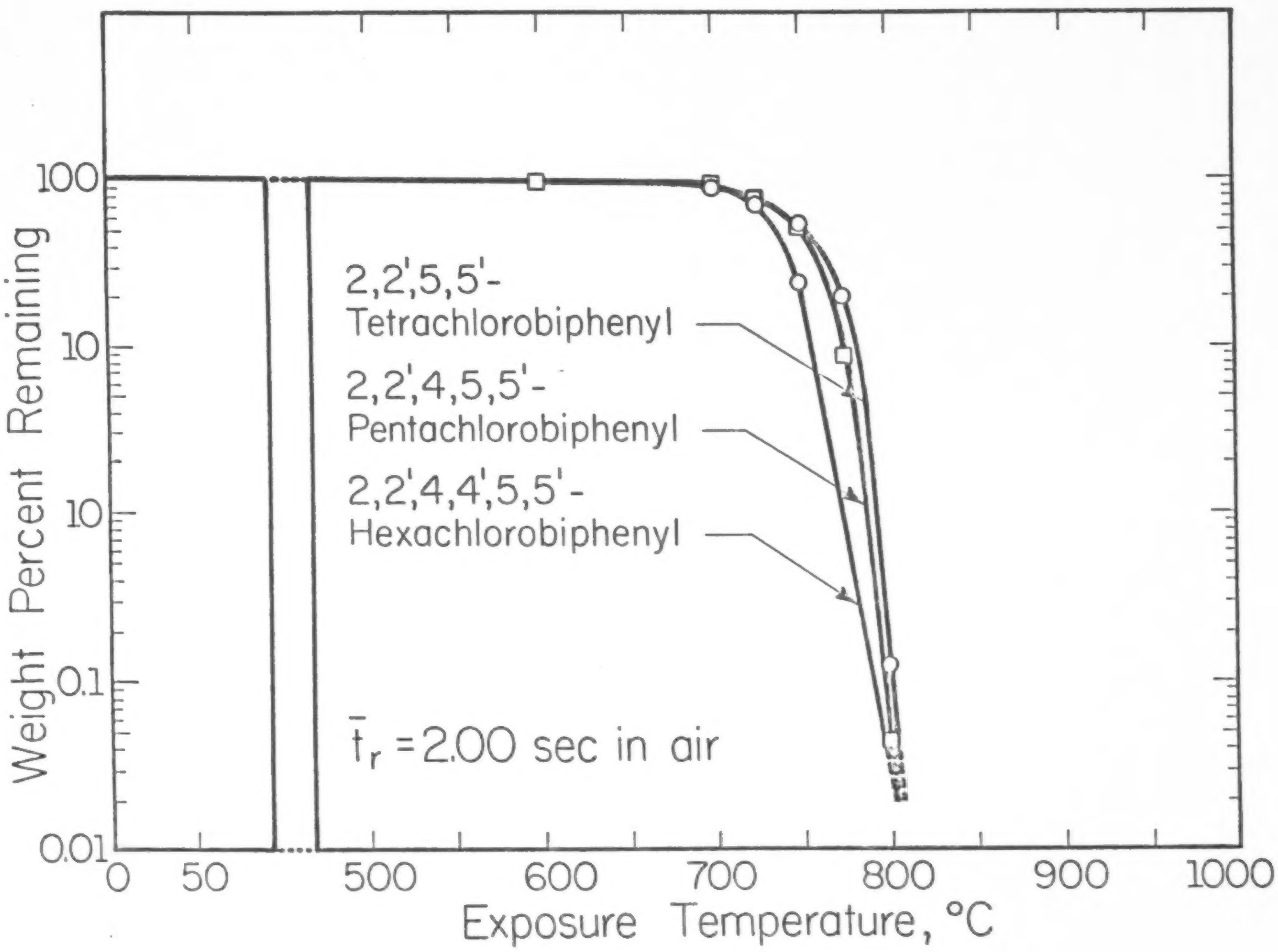


Figure 10 Thermal Decomposition Profile of PCB Isomers (17)

TABLE 10. COMPOUNDS FORMED FROM DECOMPOSITION OF PCB ISOMERS (17)

	ISOMERS		
COMPOUNDS*	2,2',5,5'	2,2',4,5,5'	2,2',4,4',5,5'
trichlorobenzene	+	+	-
biphenyl	+	-	-
tetrachlorobenzene	+	2 isomers	+
monochlorobiphenyl	+	+	-
chlorinated compound MW204+	+	-	-
dichlorobiphenyl	+	+	-
pentachlorobenzene	-	+	+
chlorinated compound MW230+	2 isomers	-	-
trichlorobiphenyl	2 isomers	+	+
dichlorodibenzofuran	+	-	-
tetrachlorobiphenyl	2 isomers	+	-
pentachlorobiphenyl	2 isomers	+	-
trichlorodibenzofuran	+	+	-
hexachlorobenzene	-	+	+
chlorinated compound MW264+	-	3 isomers	-
tetrachlorodibenzofuran	-	2 isomers	-
hexachlorobiphenyl	-	+	+
heptachlorobiphenyl	-	-	+
pentachlorodibenzofuran	-	-	+
chlorinated compound MW288+	-	-	+

+ = tentative identification

- = not found

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*Flowing air, 725°C, and residence time of 2 sec.

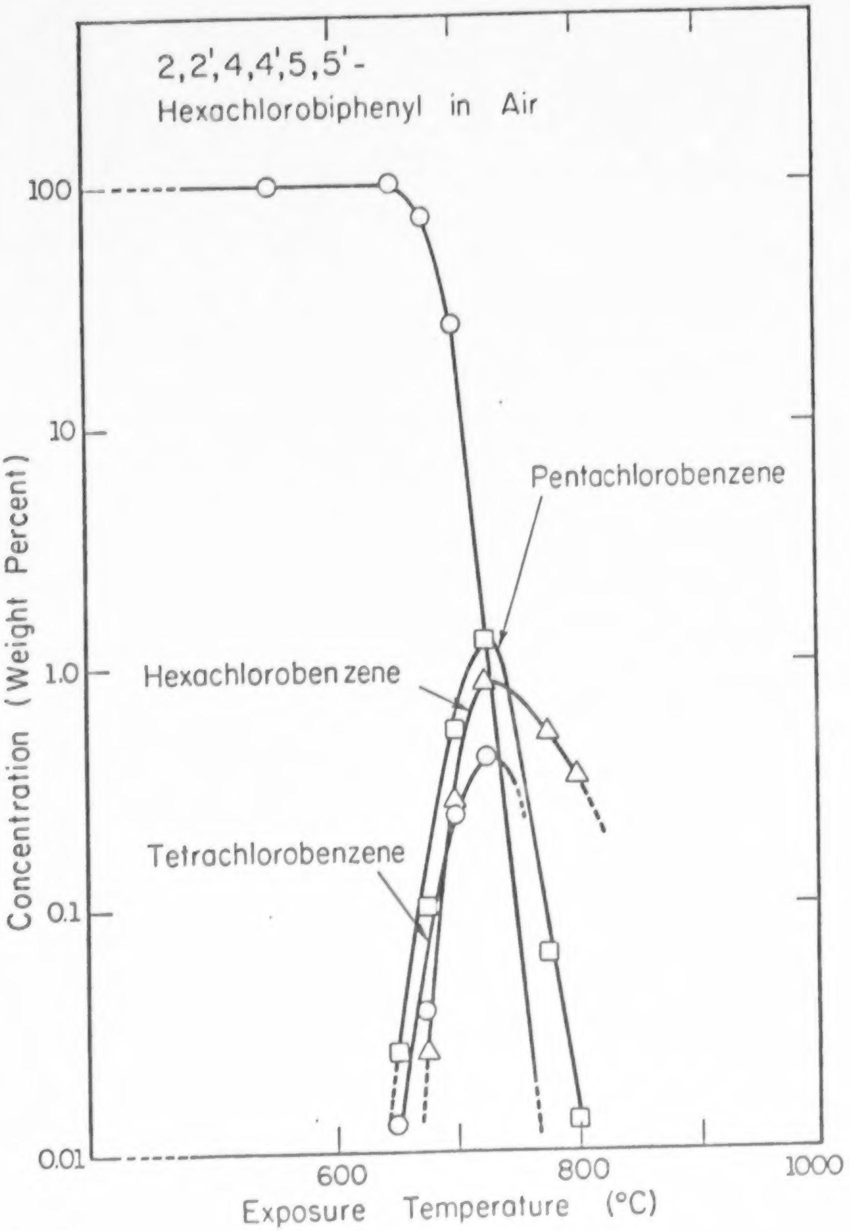

Figure 11 Decomposition Products of Hexachlorobiphenyl (17)

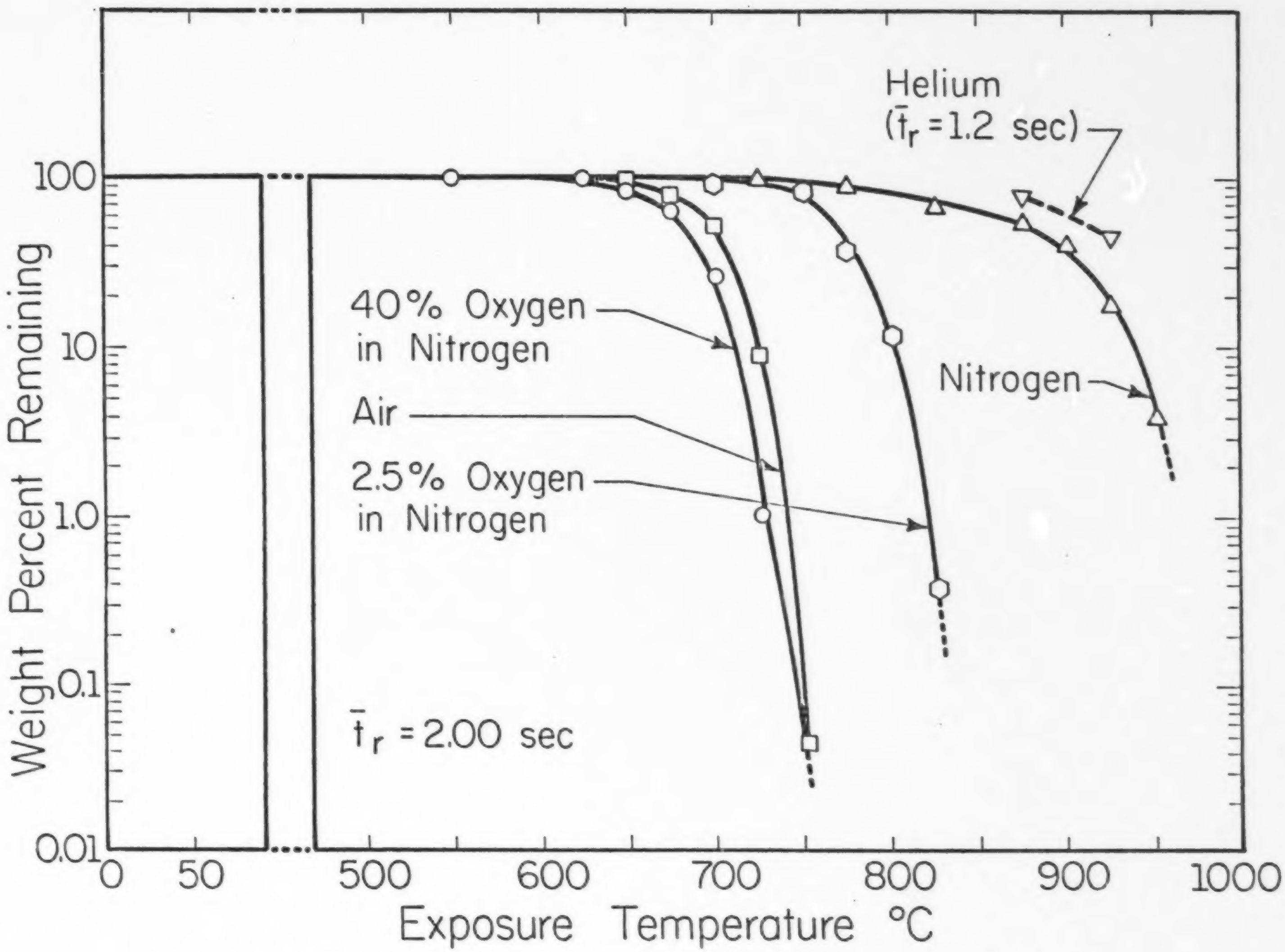

Figure 12 Thermal Decomposition of 2,2',4,5,5'-Pentachlorobiphenyl in Different Gaseous Atmospheres (17)

and 40 percent O_2 were quite small; however, when proceeding in the direction of oxygen starvation, or pyrolytic decomposition, temperatures required for decomposition exceeded those in air by more than 200°C.

The term "hex" wastes has been associated with residues and still bottoms resulting from the processing of hexachlorocyclopentadiene and various other closely associated precursor chemicals. The exact composition of the "hex" wastes is continually changing as this complex chlorinated hydrocarbon mixture is unstable. The major components of a typical "hex" waste are given in Table 11. Thermal decomposition profiles resulting from "hex" waste thermal decomposition experiments are shown in Figure 13. "Hex" wastes can be seen to require high temperature oxidative conditions for complete decomposition as they contain, and even generate, sizeable quantities of the very stable hexachlorobenzene (HCB). Perhaps one of the more profound observations is that there is a definite increase in the concentration of HCB after the first few thermal exposures as compared to its concentration in the "non-decomposed" sample (see curve "c" in Figure 13). Those HCB molecules that were formed at some intermediate point during the traverse through the reactor experienced a shorter time of high temperature exposure than did those molecules present in the original "hex" waste mixture. The most abundant low molecular weight compounds that were formed during the decomposition of "hex" waste were identifed as hydrogen chloride, chlorine, phosgene, water, methane, carbon dioxide, and carbon monoxide. It is apparent that some of these gases are of such a nature that suitable scrubbing, neutralizing, or containment measures would be required in any incineration of "hex" wastes.

Tests with a commercial polybrominated biphenyl mixture, Firemaster BP-6, demonstrated that these high molecular weight PBB compounds possess a high degree of thermal stability in an air atmosphere. Further, these tests have

TABLE 11. MAJOR COMPONENTS OF "HEX" WASTE (17)

Designation	Compound	Empirical Formula
a	hexachlorocyclopentadiene	C_5Cl_6
b	octachlorocyclopentene	C_5Cl_8
c	hexachlorobenzene	C_6Cl_6
d	pentachlorobenzene	C_6HCl_5
e	hexachloroindenone	C_9Cl_6O
f	heptachloronaphthalene	$C_{10}HCl_7$
g	octachloronaphthalene	$C_{10}Cl_8$

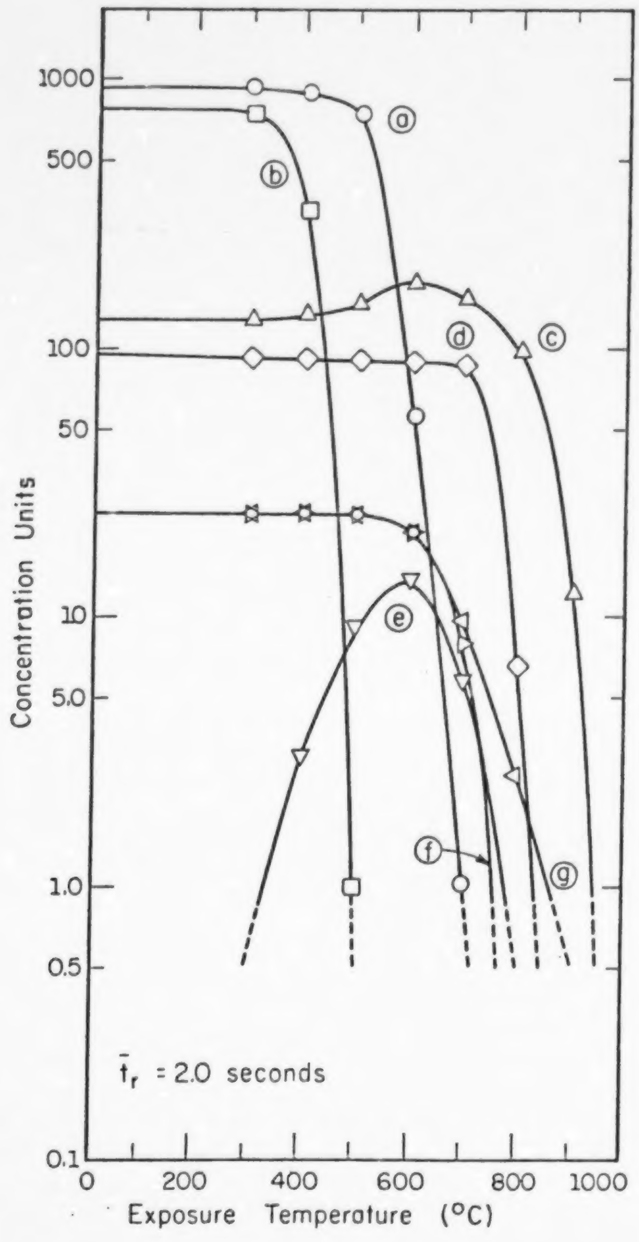

Figure 13 Composite Thermal Decomposition Profiles of "Hex" Waste (17)

shown the thermal stability of PBB isomers to be very similar to that of PCB's.

Thermal decomposition tests with Kepone, an organochlorine pesticide, demonstrated that it was more than 99.9 percent destroyed at 500°C in air at a residence time of one second. The major decomposition products of thermally stressed Kepone are hexachlorocyclopentadiene (HCCPD), hexachloroindenone (HCI), and hexachlorobenzene (HCB). These intermediates are considerably more thermally stable than the parent Kepone. Thermal decomposition profiles resulting from the Kepone experiments are shown in Figure 14.

The gas phase kinetics of the thermal decomposition of a PCB isomer, 2,2',4,5,5' - pentachlorobiphenyl in air (1000:1 mole ratio excess oxygen) over the temperature range 650°C to 750°C has been studied using the TDAS. It was determined that the thermal decomposition proceeds according to a pseudo-first-order rate equation, with a value of the Arrhenius constant of 2.26×10^{13} sec^{-1}, and an activation energy of 62.1 kcal $mole^{-1}$. The study was performed by monitoring the decrease in PCB isomer at experimental conditions. Identification of the products formed as a result of decomposition is a difficult problem for a molecule of this complexity and hence a reaction mechanism could not be postulated.

Laboratory scale thermal destruction tests have also been performed by the Union Carbide Corporation (7) in a system similar to that used by the University of Dayton Research Institute. The two systems have in common the following characteristics: bench scale, premixing of organic and air prior to heating, vapor phase reaction, low organic concentration, non-flame heating, oxidation only (no pyrolysis), chemicals only (no municipal solid waste or sludge), and non-catalytic. The Union Carbide Corporation modifications include the use of a three-zone Lindberg furnace, a 0.9 mm bore quartz tube, a

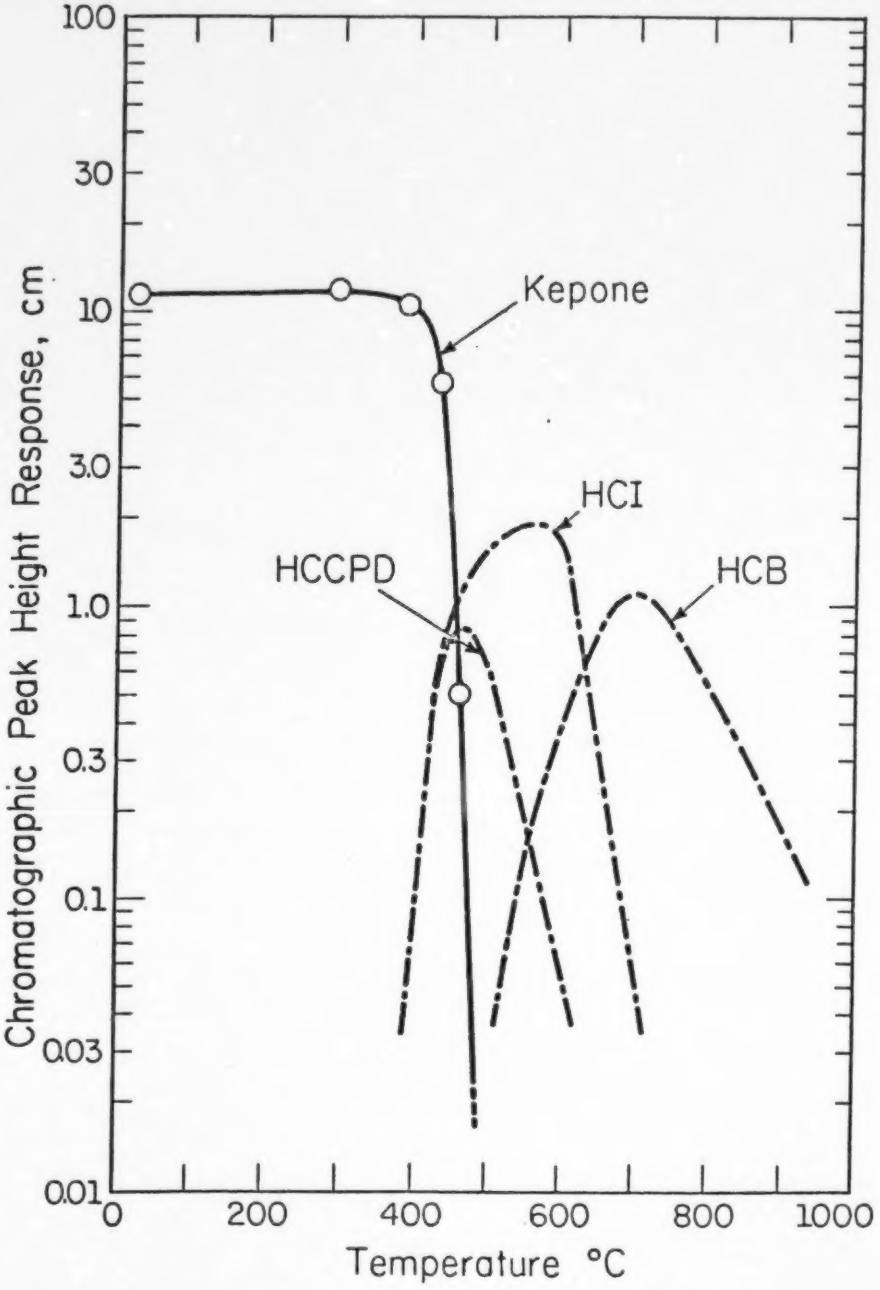

Figure 14 Thermal Decomposition of Kepone (17)

slightly different reactor configuration, a volume of about 0.8 cm^3, and rapid quenching of the combustion product gas (7).

Union Carbide Corporation (7) has developed thermal oxidation vapor phase kinetics and thermal destruction models from their experimental data. The chemicals studied in these experiments are listed in Table 12 in decreasing order of thermal oxidation stability, with methane being the most thermally stable and acrolein the least. During the experiments, all compounds were studied at 1000 ppm_v. In addition, some of the compounds were studied at 100 and 500 ppm_v; these tests gave good agreement with the 1000 ppm_v tests. The temperatures studied ranged from 800 to 1500°F and residence time from 0.1 to 2 seconds. Analyses were done for both specific chemicals and total hydrocarbons.

Union Carbide Corporation (7) presented equations for predicting thermal oxidation destruction efficiencies based on molecular structure, residence time and autoignition temperature. The predictive equations were developed from a multiple linear regression of the thermal oxidation data for the chemicals tested. The equations are of the form:

$$T = C_0 + C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_4 + C_5 X_5 + C_6 X_6 + C_7 X_7 + C_8 X_8 + C_9 X_9 \quad (1)$$

where T = temperature required for a given degree of destruction (°C);

C_0 through C_9 are constant coefficients;

X_1 = number of carbon atoms per molecule;

X_2 = aromatic compound (0 = no, 1 = yes);

X_3 = carbon double bond (0 = no, 1 = yes);

X_4 = number of nitrogen atoms per molecule;

X_5 = number of oxygen atoms per molecule;

X_6 = number of hydrogen atoms/number of carbon atoms;

TABLE 12. LIST OF CHEMICALS EVALUATED BY UCC FOR THERMAL OXIDATION KINETIC CONSTANTS (7)

Listed in order of decreasing stability with methane being the most stable.

Methane

Vinyl chloride

Ethane

Benzene

Acrylonitrile

Toluene

Propane

Ethylene

Propylene

Ethanol

Butene

1,2-Dichloroethane

Ethyl acrylate

Triethylamine

Acrolein

X_7 = non aromatic carbon double bond, chloride interaction
(0 = no, 1 = yes);
X_8 = autoignition temperature (°C);
X_9 = ln (time) (seconds).

Coefficients for the prediction of the temperature required for 99 percent (T99), 99.9 percent (T99.9), and 99.99 percent (T99.99) thermal destruction efficiency are presented in Table 13. Multiple correlation coefficients of greater than 0.98 were achieved for each of the three temperature models in the Union Carbide Corporation work. However, the most significant parameter in Eq. (1) was the non-structural autoignition temperature (AIT). The maximum multiple correlation coefficients which could be obtained solely on the basis of the structural parameters and residence time were approximately 0.20. Therefore, Eq. (1) is primarily dependent on AIT with structural parameters used to "fine tune" the model.

Although Eq. (1) fits the data for the 15 compounds studied by Union Carbide, caution must be used before applying these equations to compounds having structures which are significantly different from any of those in the data base. For example, no sulfur or phosphorus containing compounds and no highly chlorinated organics were included in the original data base. A great deal of effort could conceivably be expended in attempting to predict thermal stability solely from molecular structural parameters. Although this would constitute the ideal case, the very limited success achieved by the Union Carbide research group in a predictive stability study from structural parameters indicates that more sophisticated models will be required and a greatly expanded data base will be necessary in order to predict thermal stability for a wide array of organic chemicals.

TABLE 13. EQUATION (1) CONSTANTS FOR PREDICTIVE MODELS OF DESTRUCTION TEMPER[illegible]E (7)

Independent Variable	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
T 99°C	330.1	-7.72	80.00	38.83	44.72	-12.78	48.78	39.17	0.538	-35.94
T 99.9°C	352.6	-9.94	91.67	41.72	49.28	-12.61	49.83	38.83	0.523	-35.56
T 99.99°C	358.2	-10.72	97.78	45.67	53.17	-9.89	51.72	38.83	0.522	-35.17

In order to better manage agency research, permitting, and regulatory programs, the U. S. Environmental Protection Agency requested IT Enviroscience, Inc., to develop a thermal oxidation stability ranking parameter (TOSRP). The ideal TOSRP should be simple, inexpensive to obtain, obtainable in a reasonable time, and related to the destruction efficiency. As the destruction efficiency is dependent on residence time, temperature, turbulence, vaporization of the fuel and diffusion of the gases within the reactor, mass flow rate of the organic to be burned, and oxygen content within the gas feed system, among other factors, some consistent basis for comparison of TOSRP data must be used. The TOSRP for any particular chemical is referenced to the temperature required to obtain a 99.99 percent destruction efficiency for that chemical at a residence time of two seconds (T99.99/2). Linear regression analyses for the determination of the degree of correlation of T99.99/2 with various thermodynamic and physical properties have been performed by IT Enviroscience, Inc., (7) based on the data generated by the University of Dayton Research Institute and the Union Carbide Corporation. The properties considered and the results of the linear regression analysis are shown in Table 14. These results indicate a high degree of correlation between T99.99/2 and autoignition temperature and moderate correlation between T99.99/2 and ionization energy. The latter correlation may be somewhat misleading as the analysis was based on values of ionization energy determined by various laboratory techniques. Experimental determinations of ionization energy measured under standardized conditions may yield a higher degree of correlation with T99.99/2. IT Enviroscience, Inc., recommends the use of the autoignition temperature as a thermal oxidation stability ranking parameter.

Laboratory scale thermal destruction tests of pesticides were performed by TRW, (8), who determined that the slowest and controlling step in high

TABLE 14. RESULTS OF LINEAR REGRESSION ANALYSIS FOR PREDICTION OF T 99.99/2 (7)

X Parameter	Y Parameter	Regression Coefficients		Correlation Coefficient
		Intercept	Slope	
ΔH^0_{f298} (k joules/mole)	T 99.99/2	679.8	0.14	0.21
ΔG^0_{f298} (k joules/mole)	T 99.99/2	674.5	0.06	0.08
Flash point (°C)	T 99.99/2	652.6	-0.31	0.22
ΔH_c (joules/mole)	T 99.99/2	625.3	0.05	0.62
ΔH_c (joules/gram)	T 99.99/2	593.82	0.0020	0.39
E_a (k joules/g mole)	T 99.99/2	587.7	0.44	0.43
ΔH_f of ion (k joules/mole)	T 99.99/2	447.8	0.25	0.74
AIT (°C)	T 99.99/2	391.08	0.64	0.90
Ionization potential (electron volts)	T 99.99/2	355.8	33.2	0.80

temperature combustion is the oxidation of the initially formed carbon monoxide. This is not surprising since it is also the slowest step in premixed flame oxidation of ordinary hydrocarbons.

SECTION 6

EXTENSION OF LABORATORY SCALE TEST DATA TO COMMERCIAL SCALE UNITS

Pilot plant scale thermal destruction efficiency tests have been performed by B. Ahling of the Swedish Water and Air Pollution Laboratory (7). The pilot plant thermal oxidation system used for these studies has primary and secondary combustion chambers, followed by a sampling duct and a variable speed fan. The primary combustion chamber is a cylindrical, refractory-lined vertical furnace with a stationary grate at the bottom. It has the capability to handle liquid waste and/or solid waste. The furnace can use either sawmill chips or liquid petroleum gas (LPG) as auxiliary fuel or both. The systems secondary combustion chamber has a cyclonic separator configuration with a tangentially-tired LPG burner of the same type and size as in the primary chamber. Destruction efficiency tests were carried out using PCB Pyralene 3010, PCB Arochlor 1254, and hexachlorobenzene. Test conditions and results of the pilot plant studies for these compounds are shown in Table 15. Destruction efficiencies of greater than 99.99 percent were obtained for seven of the nine PCB Pyralene 3010 samples, six of 13 PCB Arochlor 1254 samples, and 11 of 13 hexachlorobenzene samples. Multiple linear regression analysis was used to investigate the reaction kinetics of the data generated in the pilot plant tests. The results of this analysis indicate that the data did not follow the Arrhenius equation and hence could not be described by using first order kinetics.

Since the pilot plant data did not fit first-order kinetics, no direct comparison of T99.99/2 values can be made between pilot and bench-scale data (e.g. TDAS data). However, it appears that the temperatures required for 99.99 percent destruction at a 2 second residence time in the pilot plant studies are 200°C to 300°C higher than the temperatures required for the same

TABLE 15. PILOT PLANT TEST RESULTS FOR THE COMBUSTION OF PCB PYRALENE 3010, PCB AROCHLOR 1254, and HEXACHLOROBENZENE (7)

Exp. No.	Feed Rate (g/h)	Furnace Temperature (°C)	Time (s)	O_2 Following The Furnace (%)	Total Unburned Reactant (mg/kg)	Destruction Efficiency (%)
				PCB Pyralene 3010		
1	127	685	1.9	14.0	1200	99.8800
2	133	690	3.0	12.5	24	99.9976
3	324	800	4.0	7.0	37	99.9963
4	379	845	1.9	8.2	8.4	99.9992
5	155	850	3.0	8.5	14	99.9986
6	306	865	3.7	2.5	41	99.9959
7	324	865	3.8	0.5	77	99.9923
8	373	985	3.7	2.0	90	99.9910
9	27	1000	1.5		380	99.9620
				PCB Arochlor 1254		
10	331	675	1.9	13.2	185	99.9815
11	122	700	3.7	12.5	225	99.9775
12	750	780	1.9	12.0	105	99.9895
13	53	780	4.8	2.5	26	99.9974
14	195	800	0.8	11.0	4610	99.5390[a]
15	195	800	1.6	10.5	230	99.9770[a]
16	270	810	4.2	6.5	38	99.9962
17	68	870	3.8	1.5	68	99.9932
18	37	925	3.8	2.5	46	99.9954
19	195	960	1.6	5.5	11	99.9989[a]
20	19	970	1.6		1540	99.8460
21	108	990	3.9	3.0	55	99.9945
22	223	1000	0.8	5.0	1085	99.8915[a]
				Hexachlorobenzene		
23	91	620	2.2	11.8	24370	97.5630
24	64	830	2.1	7.0	1235	99.8765
25	106	900	0.7	10.8	28	99.9972
26	51	900	1.3	11.1	4.7	99.9995
27	155	975	1.8	6.5	14	99.9986
28	18	985	2.6	10.0	15	99.9985[b]
29	59	1000	0.7	11.0	53	99.9947
30	39	1030	1.5	9.2	4.9	99.9995
31	59	1030	1.5	9.2	3.9	99.9996
32	42	1075	0.8	10.0	12	99.9988
33	18	1100	3.3	0.6	22	99.9978[b]
34	55	1125	0.8	8.0	28	99.9972
35	30	1125	1.6	6.0	38	99.9962

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[a] Used diesel fuel oil as solvent instead of isopropanol.

[b] Used acetone as solvent instead of isopropanol.

degree of destruction in the laboratory bench scale unit. This is not surprising as the operating conditions in most incinerators are not as simple as those in the laboratory devices. Among the potential complications associated with field-scale incinerators as compared to the TDAS system are the following (7):

(1) Wastes may enter the combustion chamber of an incinerator as liquids or solids, while only gases enter the reaction zone in the TDAS.

(2) Direct combustion of fuel and/or waste supplies the heat required for the reactions in incinerators, and the waste in an incinerator may pass directly through a distinct flame or flame front, whereas the TDAS is indirectly heated.

(3) There may be a significant lack of homogeneity in the temperature profiles of incinerators, and the temperature may not be as closely controlled as in the TDAS. Furthermore, the maximum temperature in an incinerator may be higher than the highest temperature at which laboratory devices can be operated.

(4) Residence time for an incinerator is determined by dividing the total volume of the incinerator combustion chamber by the volumetric flow rate of flue gas out of the chamber. The residence times thus determined may not be representative of the actual exposure times of the waste at the reported operating temperature. The mean residence times in the TDAS are well controlled and represent to a high degree of accuracy the true exposure times of the waste at the reported temperatures.

(5) Physical and chemical interactions between components of mixtures of wastes and reaction products might alter the rate of waste decomposition and combustion product formation. Furthermore, interaction

of the combustion products with the walls of the incinerator might effect the degree of combustion and the products. Many of these effects cannot be studied in the TDAS since only gases enter the reaction chamber.

(6) Mixing in an incinerator will be different from mixing in the TDAS, resulting in differences in the relative amounts of uncombusted, partially combusted, and completely combusted waste.

(7) In an incinerator, the conditions to which various molecules are exposed can vary greatly in terms of temperature, oxygen concentration, and concentrations of free radicals. These variables can be too complicated to simulate in the laboratory units.

(8) The TDAS is usually operated in such a manner that the amounts of oxygen leaving the reactor is not significantly different from the amounts going into the reactor. Furthermore, while many laboratory experiments were performed with 21 percent oxygen, incinerator flue gas often contains much less oxygen.

(9) The feed rate of an incinerator may be constant, allowing steady-state conditions to occur, whereas the TDAS is batch fed.

While the extension of laboratory scale test data to pilot plant data has not proved very successful for determining the temperatures required for a certain degree of destruction of a particular waste, laboratory scale data can still provide a very valuable input towards taking hazardous waste incineration out of the category of an art and making it more of a science. The actual and potential uses of a thorough laboratory scale data base include the following:

(1) The TDAS may be used as an aid in identifying the byproducts of decomposition of hazardous materials and the conditions under which they are formed.

(2) Comparison of TDAS decomposition experiment data to the results of full-scale test burn experiments under similar conditions may aid in the understanding of the detailed operating conditions within an incinerator.

(3) Data from the TDAS may be used in the development of empirical models, or as a check for theoretical thermochemical models of the thermal decomposition process.

(4) Data from the TDAS may be used in risk assessment and in research prioritization determination for hazardous waste incineration by considering the types, amounts, thermal stabilities, and toxicities of the reaction products observed.

(5) Data from laboratory scale waste decomposition experiments can provide minimum temperature, retention time, turbulence, and excess air level data for trial burn operating conditions and may be of predictive value if suitable margins of safety can be determined.

(6) Data from laboratory scale tests might be helpful in determining what to monitor at trial burns and at full-scale industrial installations.

From the standpoints of decreased cost and increased safety, it would be useful to be able to determine conditions for thermal destruction of given wastes in commercial scale incinerators from thermal destruction tests in pilot scale incinerators. This gives rise to the question that if a given waste is incinerated safely in a small pilot scale incinerator, how does one determine whether a larger, supposedly similar unit is capable of achieving the same degree of destruction? There is an urgent need to develop scaling laws for the various types of incinerators used in hazardous waste disposal. Because of material restrictions, and of contradictory demands that may be presented by each mechanism (e.g. high velocity for equivalent mixing versus low velocity for equivalent residence time), complete similarity may not be able to be achieved even in geometrically similar units. The problem is further complicated by the fact that larger units will not, in general, be geometrically scaled small units but may utilize multiple subsystems (e.g. multiple burners of the same size as that used in a smaller unit). TRW, Inc., has proposed the following as a potential definition of similarity (8):

> Two geometrically similar incinerators of different capacities are deemed similar if, when burning the same type of waste, they produce the same level of destruction and their stack gases and residues, respectively, have the same composition.

At the present time, there are no scaling laws applicable to any one of the major incinerator types. The U. S. Environmental Protection Agency is currently in the process of developing a pilot scale rotary kiln incinerator in Arkansas (7,18). Comparison of test data obtained with this unit with commerical scale rotary kiln incinerator data may provide valuable insight into the development of scaling laws for the rotary kiln incinerator.

SECTION 7

THEORETICAL ANALYSIS OF CHEMICAL REACTION MECHANISMS

Equilibrium Considerations

While mixing and kinetic rate processes determine the overall rate at which thermal destruction occurs, the ultimate products of the thermal destruction processes is controlled by equilibrium considerations. It is true that virtually all toxic materials are thermodynamically unstable at high temperatures. However, the persistance of carbon monoxide and hydrogen cyanide, for example, in the high temperature effluent from a fuel rich oxidation process is one reason why virtually all thermal oxidation processes are carried out in the presence of a large excess of oxygen. It is also true that the high temperature stability of sulfur dioxide, sulfur trioxide, hydrochloric acid gas and hydrobromic acid gas require that some type of alkaline scrubbing be used when the elements sulfur, chlorine, or bromine are present in the toxic waste that is being destroyed using a thermal method.

The above mentioned equilibrium considerations, while important to the subject of thermal destruction, are very well understood at the present time. Thus, there appears to be no need for new research in the area of high temperature equilibrium chemistry.

Studies of Detailed Chemical Reaction Kinetic Mechanisms

At the present time the detailed reaction processes that lead to the oxidation of simple molecules are reasonably well understood and developed. There have, for example, been extensive studies of the oxidation of hydrogen (19-22), carbon monoxide (23,24), methane (25,29), and methanol (30,31). The reaction sequences that have been developed for these simple compounds are relatively complex. The oxidation of hydrogen, for example, is usually performed using 18 distinct forward reactions while the oxidation of methane has been modeled by using as many as 84 independent forward kinetic steps. Also, it has been found that while the oxidation of lean fuel oxidizer systems can be modeled quite accurately using these kinetic mechanisms, the oxidation process in the fuel rich system is generally much more complex (32) and at the present time has not been represented in a satisfactory form using a series of elementary steps.

There has also been an effort recently to develop "radical pool" models of oxidation schemes to reduce the number of kinetic steps while retaining the essence of the oxidation process. This approach has proven to be successful for modeling vessel explosions (26), plug flow reaction profiles (as in the TDAS study), and flame structure, burning velocity, and limits of flammability (33,34). However, this approach is also only applicable to lean combustion of simple molecules.

The detailed studies of fuel lean oxidation of simple fuels all lead to the conclusion that the last step in the oxidation of the hydrocarbon is the oxidation of carbon monoxide to carbon dioxide by the reaction (24)

$$CO + OH \rightarrow CO_2 + H$$

This immediately leads one to the rather general conclusion that if the oxidation process has progressed sufficiently to remove carbon monoxide from the effluent gases, the oxidation process is essentially complete. This important conclusion concerning the completeness of the oxidation process has been confirmed by tests involving many different combustion systems. Figure 15 taken from Refs. (35-37) shows, for example, that for a large variety of devices, the carbon monoxide-hydrocarbon ratio in the effluent is approximately 10. The only exception to this statement applies to the incineration of gaseous effluents, diesel engines, and some gas fired and coal fired boilers. In these circumstances, if the mixing is not complete, cold,

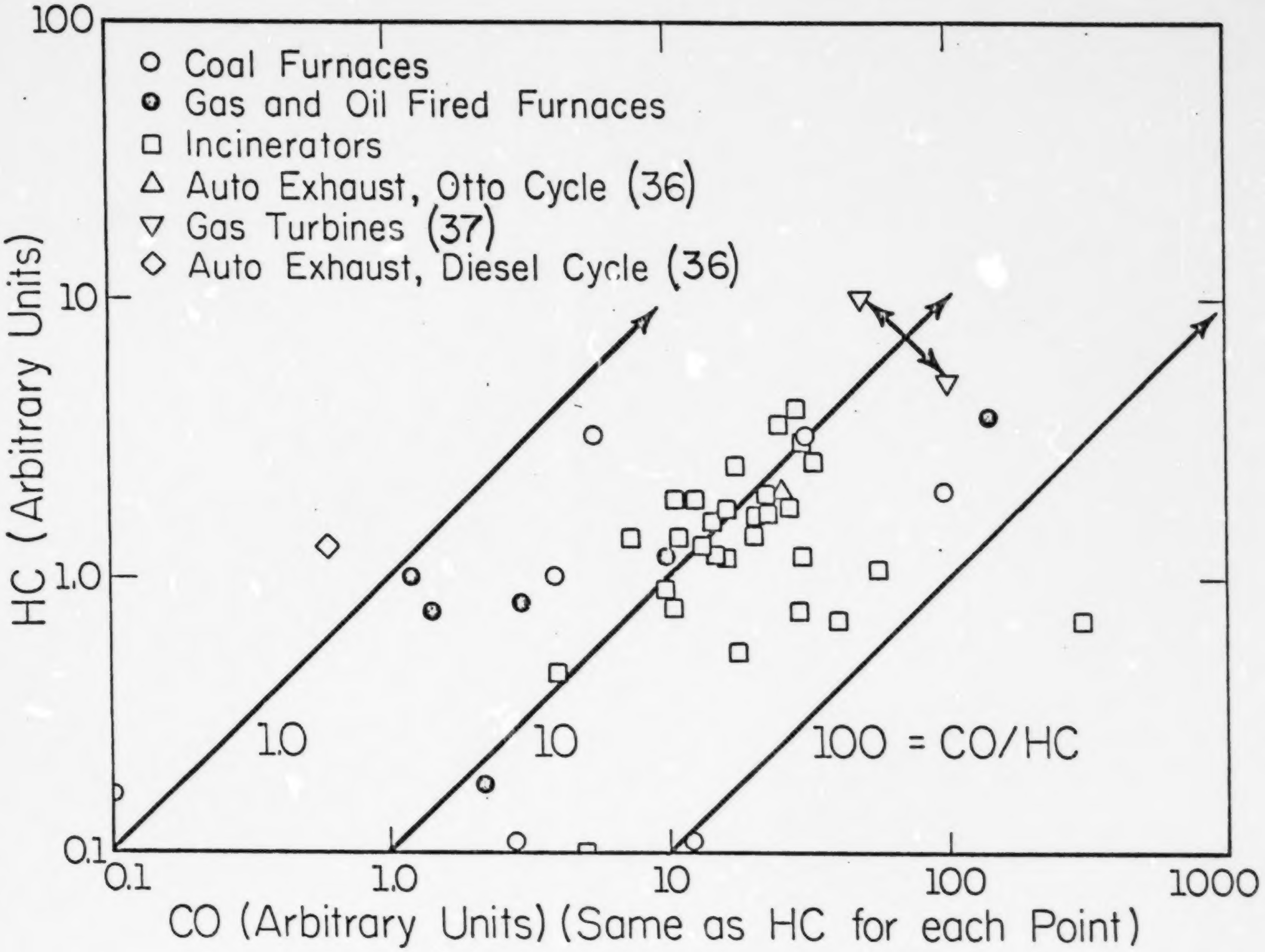

Figure 15 Relationship between Carbon Monoxide (CO) and Hydrocarbon (HC) Concentrations in Various Exhausts

unburned portions of the initial gaseous stream can go through the device without being oxidized at all and therefore the CO/HC ratio can be much less than 10. In all other cases, all portions of the mixture are at least partially oxidized and the concentration of the hydrocarbon fragments that remain after combustion, however incomplete, are very much smaller than and bear a direct relationship to the amount of carbon monoxide in the effluent.

Overall Kinetic Studies

The detailed kinetics of the pyrolysis and oxidation of more complex hydrocarbons than methane (a C_1 hydrocarbon) are considerably more difficult to model using elementary reaction kinetic steps (particularly on the fuel rich side). There has, however, been some progress in understanding these pyrolysis and oxidation processes. One of the interesting observations concerning the decomposition path that these molecules take is that they generally involve the intermediate production of higher molecular weight molecules with more carbon atoms than are in the original fuel which is being oxidized (34). This work has thus far involved the decomposition of only C_2 and C_3 hydrocarbons and it is doubtful if this trend would continue if the number of carbon atoms in the parent molecule were larger than three except in fuel-rich sooting flames (38). Nevertheless, these studies do show the complexity of higher molecular weight hydrocarbon oxidation processes (39) and lead one to the general conclusion that detailed chemical mechanisms for the oxidation of higher molecular weight hydrocarbons (and substituted higher hydrocarbons which may be toxic) will not be forthcoming in the near future. It appears, therefore, that the only proper direction that one can take relative to the study of destruction rates for complex toxic substances is an experimental one like the TDAS study that is currently being funded by the EPA (17,40).

It appears that as experimental data on the overall rate of destruction of a large variety of complex toxic molecules become available, it should be possible to interpret the data in terms of the various bond energies in the molecule. This effort, if successful, would allow one to categorize toxic substances into groups by developing a scheme to rank them baed on their ease of destruction. Work along this line has already started, particularly by attempting to correlate various properties such as the autoignition temperature to the ease of destruction in a TDAS experiment (7). Further work of this type would be very useful because once some guidelines have been established the amount of experimental testing required to characterize the ease with which one can destroy a new and somewhat different organic toxic material will be greatly reduced.

SECTION 8

MATHEMATICAL MODELING OF COMBUSTION PROCESSES

Problems with Mathematical Modeling

Efficient thermal destruction requires that the toxic fuel and the oxidizer air be rapidly mixed to the molecular level at high temperature so that the oxidation chemistry required for destruction can occur rapidly. This problem is exemplified by the discussion in Section 6 which indicated that reactor contact times for the TDAS experiments were much less than those required in larger, full-scale devices where turbulent mixing must be used to obtain the intimate contact which is necessary for chemical destruction to occur. The key to this problem is the attainment of high levels of turbulence in the reactor without paying the penalty of excessive pressure drop, which requires higher power levels for the operation of the device. A general solution to this problem is not available at the present time and our current understanding of the turbulent mixing problem, particularly when the sytem is chemically reactive, is really not well developed at all. The next sections contain a description of our current understanding and the status of current research efforts in the area of turbulent reactive mixing as applied to combustion problems, particularly in jet engine or diesel combustion. Very little systematic work has been done on the improvement of incinerator design. At the present, the approach is to search for the solution by continually adjusting the configuration of an incinerator until optimum incineration is obtained.

Turbulence Modeling in Reactive Flows

The modeling of turbulent reactive flows has been a very active field of research for approximately the last decade. A number of texts and reviews now exist (41-48) that discuss the structure and mathematical modeling of ordinary turbulence and turbulence with mixing. In addition, there are at least three texts (49-51) and four lengthy reviews (52-55), and one recent conference (56), on the subject of turbulence modeling in reactive flow situations.

Nonreactive turbulence and nonreactive turbulent mixing (or reactive turbulent mixing when there are no large temperature changes due to the reactions) appears to be quite well understood at the present time. Brodkey's text (41) gives an excellent discussion of the status of this field and L. L. Simpson (57) presents a useful discussion of various practical mixing devices as well as scaling laws for practical applications.

In the case of turbulent reactive mixing where the reaction releases considerable heat and therefore causes a large change in the density of the gas, the processes are not as well understood at the present time. Two quotes from the current review literature should be sufficient to describe the magnitude of the problem. Libby and Williams [51] conclude: "It is not possible to be very specific regarding fluid-mechanical problems because of the current uncertainities. Gradient transport is remarkably effective in many turbulent shear flows with constant density despite the absence of a fundamental basis. In turbulent reacting flows, there are reasons for additional concern for the validity of gradient transport; in some flows with significant heat release the zones of intense chemical activity are sometimes relatively thin, with the consequence that large rates of mean strain arise. Such strains suggest stresses and fluxes not accurately represented by gradient transport. Even in the absence of heat release or pressure gradient effects the chemical source term may significantly influence the description of turbulent fluxes of reacting species through fine scaled interactions."

In another recent review Oran and Boris (53) make the following statement: "The presence of turbulence alters mixing and reaction times and heat and mass transfer rates, which in turn modify the local and global dynamic properties of the system. Because turbulence is so important, we need reasonably accurate models to use in reactive flow hydrodynamics codes. The general views of the turbulence community of what these models should be are well represented in the many references given at the end of this paper. It is our belief that none of these models includes enough of the physics of expanding, variable density, transient, multiscale reactive flows to provide a reliable predictive model representing turbulence in a general code." Thus it appears that reaction turbulent flow modeling is still essentially undeveloped as a predictive tool and that a very vigorous research program will be needed if predictive capability is to be achieved.

SECTION 9

RECOMMENDATIONS

(1) Continue and expand the Thermal Decomposition Analytical System (TDAS) studies to determine T99.99/2 values and general temperature/residence time thermal decomposition data for a variety of hazardous compounds representing different molecular structures.

(2) Generate Auto Ignition Temperature (AIT) values for the substances studied in (1) and determine the degree of correlation between AIT and T99.99/2.

(3) Generate ionization energy data for the substances studied in (1) and determine the degree of correlation between ionization energy and T99.99/2.

(4) Attempt to "fine tune" the models given in (2) and (3) by bringing in the effects of molecular structure.

(5) As a part of the TDAS study, examine the concentration of carbon monoxide (CO) as a function of temperature and residence time to determine if regulations governing the thermal destruction of CO will suffice to govern the thermal destruction of all PICS.

(6) Investigate the possibility of monitoring only CO to certify an incinerator for burning toxic wastes.

(7) Continue development and implement the rotary kiln pilot plant in Arkansas and use the generated data to develop scale-up laws for rotary kiln incinerators.

(8) Develop a pilot plant as in step (6) for the generation of scale-up laws for liquid injection incineration.

(9) The newer approaches to reactive turbulent flow modeling in the presence of large density gradients should be pursued. Virtually all the extant

turbulent modeling is not predictive when one faces the realities of a turbulent diffusion flame.

(10) Fundamental kinetic studies in which individual reaction steps are identified and each of their rates measured would not be useful at this time. This is because in practical incineration turbulence so restricts the rate of the chemistry that it controls the conversion rate. Also, the combustion chemistry of large organic molecules is a very complex subject and detailed mechanisms have not been identified as yet. Thus it appears that the simple first order kinetic approach that has been used in the TDAS studies will be adequate for a considerable period of time.

REFERENCES

1. Brockway, M. E., and P. N. Cheremisinoff, "Understanding Incinerators: Part 1 - Operating Concepts and Applications of Field-erected Units," Plant Engineering, pp. 103-106, April 27, 1978.

2. Eldredge, R. W., "Industrial Solid-Waste Management," in David Gordon Wilson, ed., Handbook of Solid Waste Management, Chapter 12, Van Nostrand Reinhold Company, 1977.

3. Bonner, T., B. Desai, J. Fullenkamp, T. Hughes, E. Kennedy, R. McCormick, J. Peters, and D. Zanders, Draft-Engineering Handbook for Hazardous Waste Incineration, Monsanto Research Corporation, EPA Contract No. 68-03-2550, November 1980.

4. Shen, T. T., M. Chen, and J. Lauber, "Incineration of Toxic Chemical Wastes," Pollution Engineering, pp. 45-50, October 1978.

5. Weismantel, Guy E., "It's Mixed Reviews for New Incineration Rules," Chemical Engineering, pp. 73-77, March 23, 1981.

6. Ross, Richard D., "Burn, Hazardous Waste, Burn," Chemtech, pp. 708-712, November 1980.

7. Cudahy, J. J., L. Sroka, and W. Troxler, Incinerability, Thermal Oxidation Characteristics, and Thermal Oxidation Stability of RCRA Listed Hazardous Wastes, Draft Report, U. S. Environmental Protection Agency, Cincinnati, Ohio, 1981.

8. Manson, L., and S. Unger, Hazardous Material Incinerator Design Criteria, EPA-600/2-79-198, U. S. Environmental Protection Agency, Cincinnati, Ohio, October 1979.

9. Sittig, M., Incineration of Industrial Hazardous Wastes and Sludges, Pollution Technology Review No. 63, Noyes Data Corporation, 1979.

10. Rolke, R. W., R. D. Hawthorne, C. R. Garbett, E. R. Slater, T. T. Phillips, and G. D. Towell, Afterburner Systems Study, Report No. S-14121, Shell Development Company, 1972.

11. Khodadadi, J. M., "Thermal Degradation of Organic Materials by Pyrolysis: The State-of-the-Art," M. S. Thesis, University of Illinois at Urbana-Champaign, 1982.

12. Baillod, C. R., R. A. Lamparter, and D. G. Leddy, "Wet Oxidation of Toxic Organic Substances," Presented at Purdue Industrial Waste Conference, West Lafayette, Indiana, May 1979.

13. Hitchcock, D. A., "Solid-waste Disposal: Incineration," Chemical Engr., pp. 185-194, May 21, 1979.

14. Adams, J. W., N. J. Cunningham, E. H. Dohnert, J. C. Harris, P. L. Levins, J. L. Stauffer, K. E. Thrun, L. R. Woodland, D. G. Ackerman, J. F. Clausen, A. Grant, R. J. Johnson, C. C. Shih, R. F.

Tobias, and C. A. Zee, Destroying Chemical Wastes In Commercial Scale Incinerators: Final Report - Phase II, TRW Defense and Space Systems Group, EPA Contract No. 68-01-2966, November 1977.

15. Duvall, D. S., W. A. Rubey, and J. A. Mescher, "Laboratory Characterization of the Thermal Decomposition of Hazardous Wastes," Proc., SWRI-EPA Conf. on Land Disposal of Hazardous Wastes, EPA-600/9-78-016, pp. 104-111, U. S. Environmental Protection Agency, Cincinnati, Ohio, 1978.

16. Rubey, W. A., Design Considerations for a Thermal Decomposition Analytical System, EPA-600/2-80-098, U. S. Environmental Protection Agency, Cincinnati, Ohio, August 1980.

17. Duvall, D. S., W. A. Rubey, J. A. Mescher-Smith, and R. G. Keil, High-Temperature Degradation Characteristics of Hazardous Organic Wastes - A Laboratory Approacn, Draft Report, U. S. Environmental Protection Agency, Cincinnati, Ohio, 1981.

18. Miller, S., "Incinerator Research Abuilding," Environmental Science and Technology, Vol. 14, No. 9, pp. 1028-1029, Sept., 1980.

19. Warnatz, J., Ber. Bunsenges Phys. Chem., Vol. 82, pp. 643-649, 1978.

20. Oran, E. S., and J. P. Boris, "Theoretical and Computational Approach to Flame Ingition," Proc., Int. Colloquium on Gas Dynamics of Explosions and Reactive Systems, pp. 154-170, American Institute of Aeronautics and Astronautics, New York, 1979.

21. Dixon-Lewis, G., Proc. Roy. Soc., Vol. A298, pp. 495-512, 1967; Vol. A307, pp. 111-135, 1968; Vol. A317, pp. 235-236, 1970; Vol. A330, pp. 199-218, 1972; Vol. A331, pp. 571-584, 1973; Vol. 292, A1388, pp. 45-99, 1979.

22. Stephenson, P. L., and R. G. Taylor, Comb. and Flame, Vol. 20, pp. 231-244, 1973.

23. Warnatz, J., Ber. Bunsenges Phys. Chem., Vol. 83, pp. 950-957, 1979.

24. Cheriam, M. A., P. Rhodes, R. J. Simpson, and G. Dixon-Lewis, "Kinetic Modeling of the Oxidation of Carbon Monoxide in Flames," 18th Symposium (Int.) on Combustion, pp. 385-396, 1981.

25. Tsatsaronis, G., Comb. and Flame, Vol. 33, pp. 217-239, 1978.

26. Guirguis, R. H., A. K. Oppenheim, I. Karasalo, and J. R. Creighton, "Thermochemistry of Methane Ignition," Proc., Int. Colloquium on Gas Dynamics of Explosions and Reactive Systems, pp. 134-153, American Institute of Aeronautics and Astronautics, New York, 1979.

27. Westbrook, C. K., Combustion Sci. and Tech., Vol. 20, pp. 5-17, 1980.

28. Westbrook, C. K., J. Creighton, C. Lund, and F. Dryer, J. Phys. Chem., Vol. 81, pp. 2542-2554, 1977.

29. Smoot, L. D., W. C. Hecker, and G. C. Williams, Comb. and Flame, Vol. 26, pp. 323-342, 1976.

30. Westbrook, C. K., and F. L. Dryer, Comb. and Flame, Vol. 37, pp. 171-192, 1980.

31. Westbrook, C. K., and F. L. Dryer, Comb. Sci. and Tech., Vol. 20, p. 125, 1979.

32. Warnatz, J., "The Structure of Laminar Alkane-, Alkene-, and Acetylene Flames," 18th Symp. (Int.) on Combustion, pp. 369-384, 1981.

33. Creighton, J. R., "A Two Reaction Model of Methane Combustion for Rapid Numerical Calculations," Lawrence Livermore Laboratory, Livermore, Cal., Preprint UCRL-79669, Rev. 1, pp. 1-21, 1977.

34. Edelman, R. B., and O. F. Fortune, "A Quasi-Global Chemical Kinetic Model for the Finite Rate Combustion of Hydrocarbon Fuels with Application to Turbulent Burning and Mixing in Hypersonic Engines and Nozzles," AIAA Paper 69-68, New York, 1969.

35. Strehlow, R. A., "Carbon Monoxide from Waste Disposal," Unnumbered report prepared for the State of Illinois EPA August 13, and memo dated Sept. 1971 to G. N. Reddy, 1971. Note: Data points in Figure 15 were obtained from the following sources: Niessen, R. R., et al., Systems Study of Air Pollution from Municipal Incineration, Vol. i, A. D. Little, Inc., Contract Report CPA 22-69-23, March, 1970, pp. V35-V37, P. B. 192378; Corey, R. C., Principals and Practice of Incineration, Wiley, N. Y., 1969; Stenberg, R. L., R. R. Harsley, R. A. Herric, and A. H. Rose, Jr., J. Air Pollution Control Assoc., Vol. 10, p. 114, 1962; Stenberg, R. L., R. P. Hangebranck, D. J. Von Lehmden, and A. H. Rose, J. Air Pollution Control Assoc., Vol. 12, pp. 83-89, 1962; Hangebranck, R. P., D. J. Von Lehmden, and J. E. Meeker, J. Air Pollution Control Assoc., Vol. 14, pp. 267-278, 1964.

36. Perkins, H. C., Air Pollution, McGraw Hill, N.Y., 1974.

37. Cornelius, W., and W. G. Agnew, Eds., Emissions from Continuous Combustors, Plenum Press, N.Y., 1972.

38. Olson, D. B., and H. F. Calcote, "Ions in Fuel-rich and Sooting Acetylene and Benzene Flames," 18th Symp. (Int.) on Combustion, pp. 453-464, 1981.

39. Gal, D., L. Botar, E. Danoczy, I. P. Hajdn, K. Heberger, J. Lukacs, I. Nemes, and T. Vidoczy, "Some Aspects of Modeling Hydrocarbon Oxidation," 18th Symp. (Int.) on Combustion, pp. 1321-1331, 1981.

40. Levy, A., A. A. Putnam, H. A. Arbib, and R. H. Barnes, "Kinetics and Mixing in Industrial Afterburners," Proc., Joint Symp. on Stationary Combustion: NOX Control, Denver, Col., Oct. 9, 1980.

41. Brodkey, R. S., The Phenomena of Fluid Motions, Chapter 14, Addison-Wesley, N.Y., 1967.

42. Brodkey, R. S., ed., Turbulence in Mixing Operations, Academic Press, N.Y., 1975.

43. Bradshaw, P., ed., Turbulence, Vol. 12, Topics in Applied Physics, Springer Verlag, Berlin, 1978.

44. Fiedler, H., ed., Structure and Mechanisms of Turbulence, Vols. 1 and 2, Lecture Notes in Physics, Vols. 75 and 76, Springer Verlag, Berlin, 1978.

45. Launder, B. E., and D. B. Spaulding, Lectures in Mathematical Models of Turbulence, Academic Press, N.Y., 1972.

46. Bradshaw, P., An Introduction to Turbulence and It's Measurement, Pergammon, Oxford, 1975.

47. Schetz, J. A., "Injection and Mixing in Turbulent Flow," Progress in Astronautics and Aeronautics, Vol. 68, American Institute of Aeronautics and Astronautics, N.Y., 1980.

48. Bradshaw, P., T. Cebeci, and J. H. Whitelaw, Engineering Calculation Methods for Turbulent Flow, Academic Press, N.Y., 1981.

49. Murthy, S. N. B., ed., Turbulent Mixing in Nonreactive and Reactive Flows, Plenum Press, 1976.

50. Kennedy, L. A., ed., "Turbulent Combustion," Progress in Astronautics and Aeronautics, Vol. 58, American Institute of Aeronautics and Astronautics, N. Y., 1977.

51. Libby, P. A., and F. A. Williams, eds., "Turbulent Reacting Flows," Topics in Applied Physics, Vol. 44, Springer Verlag, Berlin, 1980.

52. McDonald, H., "Combustion Modeling in Two- and Three- Dimensions--Some Numerical Considerations," Progress in Energy and Combustion Science Ed. Chigier, Vol. 5, No. 2, pp. 97-122, 1979.

53. Oran, E. S., and J. P. Boris, "Detailed Modeling of Combustion Systems," Progress in Energy and Combustion Science Ed. Chigier, Vol. 7, No. 1, pp. 1-72, 1981.

54. Edelman, R. B., and P. T. Harsha, "Laminar and Turbulent Gas Dynamics in Combustors--Current Status," Progress in Energy and Combustion Science Ed. Chigier, Vol. 4, pp. 1-62, 1979.

55. Brag, K. N. C., "The Interactions between Turblence and Combustion," 17th Symposium (Int.) on Combustion, pp. 223-233, 1979.

56. Measurement and Prediction of Complex Turbulent Flows: Conference, held at the University of California, Davis Campus, Sept. 1-4, 1981.

57. Simpson, L. L., "Industrial Turbulent Mixing," in R. S. Brodkey, ed., Turbulence in Mixing Operations, pp. 279-330, Academic Press, N.Y., 1975.

APPENDIX

STUDIES, MANUALS, REVIEWS, CONFERENCES, AND COURSES RELATING TO THERMAL DESTRUCTION OF HAZARDOUS WASTE

STUDIES

1. Rolke, R. W., R. D. Hawthorne, C. R. Garbett, E. R. Slater, T. T. Phillips, and G. D. Towell, Afterburner Systems Study, Report No. S-14121, Shell Development Company, 1972.

2. Wilkinson, R. R., G. L. Kelso, and F. C. Hopkins, State-of-the-Art Report: Pesticide Disposal Research, EPA-600/2-78-183, U. S. Environmental Protection Agency, Cincinnati, Ohio, August 1978.

3. Miller, S., "Incinerator Research Abuilding," Environmental Science and Technology, Vol. 14, No. 9, pp. 1028-1029, September 1980.

4. Karoly, J. A., and T. J. Rittof, "Evaporation/Incineration, An Energy Efficient Operation," Chem. Engr. Prog., Vol. 77, No. 10, pp. 42-47, 1981.

5. Anon., "Test Burns Successful on Hazardous Wastes," C & EN, Vol. 59, p. 5, Aug. 24, 1981.

6. Worthy, W., "Lab Optimizes Burning Hazardous Waste," C & EN, Vol. 59, pp. 40-42, Aug. 31, 1981.

7. Worthy, W., "Hazardous Waste: Treatment Technology Grows," C & EN, Vol. 60, pp. 10-16, March 6, 1982.

INCINERATION DESIGN MANUALS

1. Recommendations for Incinerator Design, Technical Release No. 140-2, State of Illinois Air Pollution Control Board, October, 1969.

2. "Incineration," Modern Pollution Control Technology, Vol. 1, Chapter 26, REA, New York, 1978.

3. Manson, L. and S. Unger, Hazardous Material Incineration Design Criteria, P. B. 80-131964, EPA 600/2-79-198, October 1979.

4. Bonner, T., B. Desai, J. Fullenkamp, T. Hughes, E. Kennedy, R. McCormick, J. Peters, and D. Zanders, Draft-Engineering Handbook for Hazardous Waste Incineration, Monsanto Research Corporation, EPA Contract No. 68-03-2550, November 1980.

5. Gregory, R. C., "Design of Hazardous Waste Incinerators," Chem. Engr. Prog., Vol. 77, pp. 43-47, April 1981.

REVIEWS, CONFERENCES AND COURSES

1. Edwards, J. B., Combustion, Formation, and Emission of Trace Species, Ann Arbor Science Press, Ann Arbor, MI, 1974.

2. Harkman, E. E., III., Toxic Organic Chemicals-Destruction and Waste Treatment, Pollution Technology Review No. 40, Noyes Data Corp., Park Ridge, NJ, 1978.

3. Berkowitz, J. B., et al., Unit Operations for Treatment of Hazardous Industrial Wastes, Pollution Technology Review No. 47, Noyes Data Corp., Park Ridge, NJ, 1978.

4. Sittig, M., Incineration of Industrial Hazardous Wastes and Sludges, Pollution Technology Review, No. 63, Noyes Data Corp., Park Ridge, NJ, 1979.

5. 1979 National Conference on Hazardous Material Risk Assessment, Disposal and Management, Miami Beach, Florida, April 25-27, 1979.

6. Miller, S., "Hazardous Waste Management," Environmental Sci. and Tech., Vol. 15, pp. 1413-1416, 1981.

7. Miller, S., "Destroying Hazardous Wastes," Environmental Sci. and Tech., Vol. 15, pp. 1268-1269, 1981.

8. Peirce, J. J., and A. Vesilind, eds., Hazardous Waste Management, Ann Arbor Science Press, Ann Arbor, MI, 1981.

9. Torrey, S., ed., Hazardous Waste Regulations, Reinhold, N.Y., 1981.

10. Bonner, T., et al., Hazardous Waste Incineration Engineering, Noyes Data Corp., Park Ridge, N.J., 1981.

11. ASME/EPA Hazardous Waste Incineration Conference, Williamsburg, VA., May 27-29, 1981.

12. Eagleton, L. C., Chairman, National Research Council Committee on Disposal of Hazardous Wastes, National Academy of Sciences, Washington D.C., 1981-82.

13. Short Course on Industrial Waste Incineration Technology, The Center for Professional Advancement, East Brunswick, NJ, March 22-25, 1982.

14. 10th Biennial National Waste Processing Conference and Exhibit, N. Y., May 2-5, 1982.